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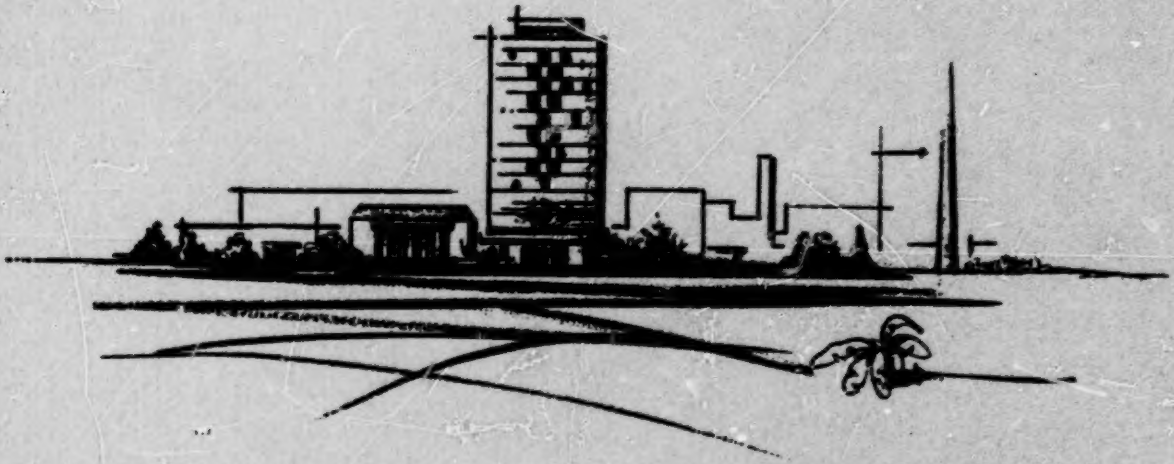

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FINAL REPORT

on

TECHNICAL-ECONOMIC EVALUATION OF AIR-POLLUTION CORROSION COSTS ON METALS IN THE U.S.

to

AIR POLLUTION CONTROL OFFICE
ENVIRONMENTAL PROTECTION AGENCY

by

F. W. Fink, F. H. Buttner, and W. K. Boyd

February 19, 1971

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SUMMARY

Two approaches were undertaken to develop a more realistic assessment of the added cost of corrosion damage to the Nation resulting from the exposure of metallic systems and structures to polluted atmospheres, both presently and by 1980. The first approach was to correlate marginal costs with air pollution levels in four metropolitan districts, each having a different average level of atmospheric pollution, covering the range from slightly contaminated to severe industrial. Because representative regional statistics for assessing corrosion damage do not exist, and the time required to develop them was found to be far beyond the limitations of the project, the first approach was dropped.

A second approach was ~~then~~ devised, employing applicable national shipment/value data from the U.S. Department of Commerce to compute average pollution costs on a national basis. Data developed by the Census Bureau in the Standard Industrial Classification (SIC) were cross checked where possible with industry-association statistics. The results were then applied to a formula, which relates value with air pollution damage to metals in use, and which makes it possible to compute corrosion damage accurately on a national scale.

The Department of Commerce statistics are broken down into thousands of metal components of varying degrees of interest, from many of no interest to some of prime interest to this study. Accordingly, the full array was put through a series of qualitative and finally quantitative screening steps to select only those systems having a high potential of economic loss due to their numbers and their in-service vulnerability to air-pollution corrosion damage.

Two calculations were considered for summing up the economic marginal cost of corrosion caused by air pollution over the typical cost in clean air service. The first method compares the extra amount of protection and maintenance expense required in polluted atmospheres to prevent serious corrosion attack. The second is the cost involved in the shortened life of the system resulting from corrosion attack in polluted air.

Individual corrosion costs were calculated for nine major categories that survived the screening. These are regarded as most sensitive to and most damaged by air pollution corrosion. The grand total of all these categories was found to be $1.45 billion. Converted to a per-capita basis, this comes to approximately $7.10 per person per year.

To estimate the probable cost to the Nation for 1980, Battelle reviewed the various factors presently influencing the total cost of air pollution corrosion damage, predicted the trends to be taken by these factors during the next decade, and integrated these effects into an estimate for 10 years hence. Changes in the amount of external metal structures subject to attack by alterations in the corrosivity of the atmosphere were taken into consideration.

The major factors affecting the corrosivity of the atmosphere are the level of pollution and the degree of moisture present. While pollution is expected to change in the next decade, the moisture level is not. From a corrosion viewpoint, the most important pollutants are sulfur dioxide. Four estimates are presented for the sulfur dioxide levels in 1980, namely:

I. If there were no regulation of pollution, the projected consumption of sulfur-bearing fuels will result in an increase in the rate of sulfur oxide pollution of about 55 percent by 1980.

II. If today's state-of-the-art in pollution control is combined with gradually increasing enforcement of air pollution regulations, the percent increase in average pollution will be only 15 percent by 1975 and dropping to 10 percent by 1980. This case takes into account the difficulties of enforcing regulations with space heating and older power plants.

III. If the present strong public demand for cleaner air continues to encourage the government authorities to accelerate both the research in the control of pollution and the enforcement of the regulations, a 40 percent average reduction in sulfur dioxide pollution over present levels could result by 1980. This case allows for some slippage in the enforcement of the regulations where offenders are not able to respond quickly because of local circumstances.

IV. If current legislation and that about to be enacted is applied without exception to all users of fossil fuels, the sulfur dioxide emissions will be reduced 60 percent by 1975 and continue at that level through 1980.

For the four cases of pollution levels discussed above, the corresponding changes in the cost of corrosion damage are:

I. Assuming a 55 percent increase in pollution, the annual marginal loss on a per capita basis would increase about 30 percent, namely from a current level of $7.10 to $9.22 for 1980. The corresponding annual loss would increase from the present $1.45 billion to $2.1 billion by 1980.

II. In the case of a 10 percent increase in pollution, the per capita loss would rise from the present $7.10 to $7.63 by 1980. The annual loss for the Nation would increase during the decade by approximately $0.3 billion to $1.73 billion by 1980.

III. With a reduction of 40 percent in pollution, the per capita cost would show a significant drop from today's level of $7.10 to $4.36 by 1980.

IV. With a reduction of 60 percent in pollution, the per capita cost will drop from the present value of $7.10 to $2.20 in 1980. The annual loss for 1970 of $1.45 would be reduced to $0.5 billion or a savings of about one billion dollars ($4.30 per capita).

Much depends on how the interacting factors, which affect the costs of air pollution corrosion damage, follow predicted trends. The most likely impact of pollution to the Nation's economy will range between an increase of $0.3 billion to a savings of $0.5 billion over current costs.

INTRODUCTION

The Air Pollution Control Office (APCO) of the Environmental Protection Agency has been cognizant for some time of the damaging effects of pollution not only to health, to the ecology, to the climate and to air navigation (i.e., low visibility), but also to the increased corrosion of metals and to the deterioration of materials in general. APCO has been developing information on the burden to the Nation's economy of these many adverse effects of pollution. To provide a more direct estimate of the cost to the Nation's economy, specifically resulting from the increased corrosion damage to metals by exposure to polluted air, APCO sponsored this investigation to develop information on the magnitude of such loss. This information is needed as a part of the overall picture of the damage costs of air pollution to guide both those responsible for establishing pollution controls and to demonstrate to those in a position to originate legislation the need for appropriating funds to provide for developing solutions to the problems. In other words, the reduction of the corrosivity of the atmosphere will involve expenditures for developing the technology of control and for the enforcement of such controls. It must be shown that this expense will be partially recoverable in terms of reduced losses from corrosion damage to external metal structures.

It should be mentioned that atmospheric pollution may play a role in catastrophic failures caused by corrosion, such as stress-corrosion cracking. This item is excluded from the investigation. Also indoor atmospheres naturally reflect the pollution outside. Electrical contacts and electronic components may deteriorate and cause malfunctioning of equipment. This situation is recognized but in order to confine the scope to more manageable proportions is excluded from this study but is the subject of two other APCO studies.(1,2)

Limited to those metals most subject to air-pollution corrosion damage in the atmosphere, the overall objective of this investigation is to develop a realistic assessment of extra service costs due to the corrosive attack of air pollutants. More specifically, the major objectives can be stated as:

(1) Assess the total economic loss to the Nation in dollars resulting from the increased corrosion damage of externally exposed structures or systems caused by the presence of man-made pollutants in the atmosphere.

(2) Establish from predicted changes in population, industrial activity, technology of pollution control, corrosion prevention, external structures, and air pollution regulation the probable size of this economic loss in 1980.

STUDY STRATEGY

Both economic and technical sources of information were reviewed in developing the plan of investigation.

(1,2) References are given at the end of the report.

Economic Framework

The economic framework of this study derives from conventional corrosion cost studies of systems in general service. Air pollution is only one of many corrosive elements in the "general service environment", which may include wind borne mists, fumes, erosive dusts, fungi, and salt particles, etc. This study narrows down to only the cost of the man-made air pollution component of the array of damaging environmental components in the service environment.

Although defined in this respect, the study expands beyond the usual by including all service conditions wherein air-pollution attack is not masked by other more damaging service conditions.

Conventional Corrosion-Cost Evaluations

Corrosion-cost estimating was pioneered by Uhlig(3) who based his calculations directly on material lost in the corrosion process, and indirectly on the cost consequences of such material losses in systems in service. Indirect costs, he concluded, could not be estimated and were dropped. Direct costs could be accounted for in several ways, namely marginal costs of over design, coatings, water conditioning, maintenance, and parts replacement.

Subsequent authors essentially deal with elaborations on parts of Uhlig's comprehensive calculations. For example, Keynes(4) develops an equation on the economic tradeoff, the indifference curve, between maintenance and replacement, based upon the "corrosion proneness" of parts in a given corrosive service environment. Harvey(5), in a similar consideration, concludes that more economical protection can be provided with an "exterior corrosion allowance", or extra surface material as a substitute for paint.

In an attempt to assess the relative damages caused by air pollution on all materials, Salmon(4) computed the cost of material lost in the corrosion process, by a formula that assigns value to the lost metal. The metal lost is computed in weight, valued at mill product prices plus the added value (labor, expense, etc.) of converting the mill product into a finished shape and installed.

Although Salmon follows an intriguing rationale to separate out only air pollution corrosion, he tacitly accords equal value to all exposd surfaces and all metal lost by corrosion. Even though he separates out the cost of cleaning a smudged surface discolored by air pollution constituents, his calculations appear to overstate the costs.

Uhlig appears to tacitly assume that if it weren't for corrosion, uncoated plain carbon steels would do. Thus the cost of upgrading into alloy steel, and coating with phosphate, zinc, cadmium, paint, plastic etc. can be billed against corrosion. Because many of these extra measures are taken for extra corrosion reasons, Uhlig's calculations appear to quite overstate the costs in terms of this study.

Applicability to Air Pollution Problem

In this study, the objective is to calculate the real cost of air pollution corrosion to metals in existing systems. Here the real cost is equivalent to the decline in real value of such systems due primarily to air pollution corrosion, and not to other forces of deterioration. This is a more limiting objective, chosen to produce results comparable to real property valuation.

The value of real property as conventionally established or appraised by professional assessors, is accepted by the courts, the tax collectors, and in the market place. Such wide acceptance gives reality to professional appraisals. Therefore if one is to measure a "cost to society" of air pollution, it should, to be realistic, be acceptable to assessors and consistent with their appraisal formulas.

It is evident that none of the previous formula for measuring corrosion costs have premises compatible with appraisal formula. Thus, while previous estimates may have meaning to engineers and others, they have little significances in the practical world of real property value. For these reasons this study derived its own formula compatible with conventional real property valuation criteria.

Derivation of an Evaluation Formula

Air pollution corrosion affects a part of the assessed value of real property. Normally real property has two components, its capital value plus its inherent ability to create wealth over its remaining lifetime. Thus, for example, the value of a hotel is the sum of its discounted productive income, for the rest of its useful lifetime, less maintenance and operating costs for the same period, plus its capital value of the moment. In this case air pollution could affect productive income, most visibly if it were a resort hotel suddenly beneighbored by an oil refinery. The income of a residential hotel in a city might also decline as air pollution increases. However, income for a commercial hotel might increase with air pollution, as it signals increased commercial activity in the vicinity.

There is still other real property with wealth-creating capacity totally insensitive to air pollution. For example, warehouses, service stations, office buildings, and many other commercial establishments, particularly those serving industry, are quite free of income delimitation due to local air pollution.

From all appearances, the affect of air pollution on real property income, or utility, or another essential benefit can be positive or negative, but mostly neither in the nation as a whole. Thus it is assumed here that this effect balances out to zero, an assumption nonetheless worthy of further study on a regional basis.

The capital value of real property appears affected by air pollution in two ways. First, it increases maintenance costs, by impelling the owner of the real property to paint certain components more often, to regalvanize some more frequently, or to replace them entirely. Second, it may shorten the assessed life of the property or system, by causing either an earlier overall disfunctioning or exhibiting evidence of excessive maintenance on components,or both. In the former case, it is replaced earlier, and in the latter, written off earlier. In either case, the margin of shortened economic life is a real cost of air pollution to the owner.

A third possibility is to avoid the extra maintenance and shortened life of real property resulting from pollution by substituting resistant materials for the susceptible ones. This practice usually increases the original capital cost which can be assessed to the cost of pollution.

In any case, air pollution can cause a loss in value of a real property system, such as a bridge or warehouse, by promoting corrosion at some surface in components of the system, a vital structural member or a downspout. Thus the problem of deriving an evaluation formula is in dealing with extremes, i.e., to measure a corrosion phenomenon at a surface (a microcosm) and relate it to an overall system value (a macrocosm) where appraisal formulas and assessors' judgments operate. An additional problem is to recognize that all surfaces of the same metal are not of equal value in different systems, or in identical systems of different ages.

For example, in the first case, the steel surface of a I-beam on a bridge might have less influence on the bridge's value than the same amount of steel surface on a cable or bolts on the same bridge, as far as the functional integrity of the bridge is concerned. Similar comparisons can be drawn across systems, such as an eaves trough on a house compared to a transformer casing. Corroding surfaces vary in value loss depending on where they are located.

For example in the second case, the steel surface on a new, original water drainage subsystem on a new building is more valuable than the same surface on a replacement subsystem on a fully depreciated building. Because a new downspout on a condemned building is as worthless as the building, its corroding surface represents no value loss whatsoever, except possibly in salvage value if recovered.

Still another condition affects the value loss of a corroding surface. If the surface is on a system component that is subject to such additional effects as erosion, acid spills, denting and distortion forces, the value loss due to air pollution corrosion is masked by such other deteriorating forces encountered in service.

Finally, there is the superimposed situation of rapid systems obsolescence. If the rate of surface loss is slow compared to the rate of system devaluation, such as a temporary fence, the cost of air pollution corrosion is negligible. Some systems in this category suffer instant total depreciation upon first use, such as tin cans, and garbage cans, in which case no value loss can be charged to surface corrosion.

Thus the value of a surface and accordingly its corrosion cost varies widely with the component upon which it appears, and the system in which that component appears. Any value formula for systems, therefore, must make provision for these differences. This is about the limit one can go starting with a deteriorating surface and rationalizing its impact on a system's value. To develop a formulated rationale one must start with the conventional assessor value formula for real property systems and work back toward a surface.

Fundamentally, there are three general approaches to the appraisal process, which in general are pursued as cross checks, and in specific are taken as basis for judgment or points of departure in assigning value. The first approach is the market data approach in which the value of a specific property is compared with the value received in a recent sale of similar property in the same locale.

The second approach is the income approach in which the value is related to revenue minus upkeep plus depreciated capital value of the property. The third approach is the depreciated replacement cost approach, which is a variant of the second approach, i.e. the same except it depreciates from present replacement costs rather than original capital cost some years back.

In all cases average depreciation, increased by rough service or decreased by benign service, plays a fundamental role in assessing value. Average depreciation is taken by year to be equal to the original cost divided by useful average lifetime, i.e., so-called straight line depreciation. There are three variants around this base, namely, 150 percent or 200 percent declining balance method, and sum of the years-digits method. The variants either extend or shorten the effective lifetime of the real property system for tax purposes. For purposes of assessment, straight line depreciation is usually the starting point. It is represented by the assessor's formula (1) for real property systems as follows.

$$V_{st} = V_{st_0} \times D_{st}$$

$$V_{st} = V_{st_0}\left[1 - k\left(\frac{dV}{dt}\right)t\right]$$

where V_{st} = value at present time, t.

V_{st_0} = original value at time of purchase, t_0.

D_{st} = depreciation factor for the system at time, t.

$\left(\frac{dV}{dt}\right)_s$ = annual rate of depreciation of the system

k = constant $<1,\ 1,\ >1 \rightarrow \frac{dT}{dV}$

The annual depreciation rate is determined by dividing the original value of the system by its lifetime years, according to standard tables (IRS procedure 62-21).(7) The constant k is the judgment factor effectively used by the assessor to factor in departures in the condition of real property at time, t, from the average expected condition at that time. For example, evidence of heavy use of the property raises k to a point above unity so that V_{st} falls below average. Evidence of light use lowers k, so that V_{st} rises above average, if a piece of real property becomes suddenly obsolete, suffers catastrophic failure, or total destruction, k approaches $\left(\frac{dt}{dV}\right)_s$ and V_{st} approaches salvage value, or zero value in its intended purpose.

Of course, the deleterious effect of air pollution would raise k. In no case in the memory of assessors contacted in this study has an effective increase in k been directly attributed to air pollution corrosion, as it might have been through excessive wear, obsolescence, declining neighborhood etc. The reason is that real property suffers clean air corrosion and any added effect of air pollution corrosion is missed by charging up the observed condition to poor maintenance. Thus, among the deteriorating factors that are traditionally identified as affecting property values, air pollution corrosion of metals is lost among the secondary effects, and not identified as such.

Because it is less important in the value accounting of equation (1), it does not mean that air pollution corrosion is not finite. It means that air pollution corrosion cost is seldom identified as significantly shortening the useful life of real property. But if the effect is finite, it must appear somewhere else, and it does--in the maintenance costs charged against the systems benefits and/or wealth creating capacity over its lifetime.

Thus, if one is to quantify rigorously air pollution corrosion losses, a more precise concept and equation is needed.

Conceptually, a real property system can be viewed as an assembly of components, each with its own susceptibility to corrosion, its own intrinsic value, its own useful lifetime, etc. It is the component that is affected directly by air pollution. Its separate decline accordingly in functional and capital value indirectly affects that of the real property system. This concept leads to the more precise general equation (2) as follows.

Equation (2) $$V_{st} = \left[\sum_{c1}^{cn} V_{ct_0}\right] \times D_{st}$$

where V_{st} = value of the real property system at time, t.

D_{st} = depreciation factor for the system at time, t.

V_{ct} = value of system components

and $$V_{st_0} = \sum_{c1}^{cn} V_{ct_0}$$

The summing up of the value for all components would lead to the value of the system at t_0, or when the system is new. Despite the fact that components per se might have a different depreciation rate than the system does, they are normalized to the rate of depreciation of the system the components are in. That is, components may inherently depreciate faster or slower, according to design, than that of the system it is in. Components that inherently depreciate faster require maintenance to keep them up, or periodic replacement. Maintenance outlays compensate for the difference. For example, the original galvanized eaves and downspouts on a house require repeated painting during the lifetime of the house to keep these faster depreciating components up to the slower depreciation of the house. A replacement component, however, takes an initial depreciation upon installation.

Components that inherently depreciate slower, such as copper eaves and downspouts, nonetheless carry the faster depreciation of the system. Over design loss makes up the difference, as these still useful components ultimately come tumbling down with the others under the wrecker's ball.

Therefore, a system is comprised of over designed components and under designed components. The value of an over designed component is according to equation (3).

Equation (3). $$V_{ct} = V_{ct_0}\left[1 - k\left(\frac{dV}{dt}\right)_s t\right]$$

where V_{ct} = value of the component at time, t.

V_{ct_0} = value of the component new

$\left(\frac{dV}{dt}\right)_s$ = depreciation rate of the system in which the component appears

k = constant, $<1,\ 1,\ >1 \rightarrow \left(\frac{dt}{dV}\right)_s$

The constant k is unity, where components face an average service environment. It is less than unity for more benign service environments, and greater for malign ones. Approaching $\frac{dt}{dV}$ for catastrophic failure conditions, it is noted that the ratio $\left(\frac{dV}{dt}\right)_s$ is the limiting depreciation rate when that for the component is less than for the system.

The value of an under designed component is according to equation (4).

Equation (4). $V_{ct} = V_{ct_0}\left[1 - k\left(\frac{dV}{dt}\right)_c t\right]$

where all factors are the same as in equation (3), except that the $\left(\frac{dV}{dt}\right)_c$, the component's depreciation rate is a number greater than $\left(\frac{dV}{dt}\right)_s$.

To keep the component functioning at the value level of the system it is in requires maintenance or protective coatings, such as paint, galvanized, terne plate, etc. If maintenance restores the functional value of the component over the lifetime of the system, a compensating term must be added to equation (4), as follows, assuming maintenance cost is equivalent to the functional value of the maintenance.

Equation (5). $M = np$

where M = functional value of the maintenance coating

n = number of coatings required over the lifetime of the system

p = the cost of coating.

Thus, the value at any time of an under designed component is according to equation (6) as follows.

Equation (6) $= V_{ct} = V_{ct_0}\left[1 - k\left(\frac{dV}{dt}\right)_{c'} t\right] + np$

where $\left(\frac{dV}{dt}\right)_{c'}$ because of the effect of the coating, is a presumably lower depreciation rate than $\left(\frac{dV}{dt}\right)_c$,without the prime, but variable in time depending on the rigour with which the owner adheres to an adequate maintenance schedule.

The number of maintenance recoatings, n, is according to the judgment of the owner. It may be zero, if V_{Ct_o} is low and $\left(\frac{dV}{dt}\right)_{c'}$ is high, in which case other replacement is cheaper than maintenance or maintenance value is less than maintenance cost.

Finally, the value of a system in terms of the integrated value of its components is as shown in equation (7) as follows.

Equation (7). $$V_{st} = \sum_{C_{o1}}^{C_{on}} V_{Ct_o}\left[1 - k\left(\frac{dV}{dt}\right)_s^t\right] + \sum_{C_{U1}}^{C_{Un}} V_{Ct_o}\left[1 - k\left(\frac{dV}{dt}\right)_{c'}^t\right] + np$$

where C_{on} = number of overdesigned components

C_{un} = number of underdesigned components.

The effect of air pollution corrosion cost shows up in equation (7) by increasing k's which diminishes the lifetime of components, and by increasing n in the nP terms which increases maintenance.

Evaluation Strategy

Because the bulk of real property value in building systems is tied up in unexposed metal and exposed nonmetal components, the effect of even high k's and n's, for exposed metal components in equation (7), on the systems' value is relatively small. Thus assessors should be expected to relegate atmospheric corrosion to secondary importance. However, the bulk of real property value in many other construction systems is tied up in exposed metal components, in which cases the effect of high k's and n's on these systems value is relatively large.

All systems exposed to the atmosphere fall somewhere between these extremes. Each system is a separate case calling for individual assessment. To

Technical Framework

Out of the vast data and theory of corrosion, only that pertaining to the air-pollution problem is applicable to this study. Many of the numerous metal corrosion mechanisms studied, and metal-protection practices developed deal with more severe corrosion environments than would be normally expected in the average living atmospheric environment.

Even metals exposed to clean air environments may suffer sufficient damage to require protective measures notably painting, galvanizing, or otherwise providing a protective coating.

Metal-Corrosion Mechanisms

A moist climate is essential for the atmospheric corrosion of metals, such as iron and zinc.(8,9) Corrosion attack on iron begins at a threshold humidity of above 80 percent and increases proportionately thereover. Once a rust coat has formed, however, the attack will continue at some lower threshold humidity. Added to humidity, air pollution synergistically increases the rate of attack, and further reduces the threshold humidity.

Man-Made Pollutants

The most commonly found primary air pollutants are carbon monoxide, sulfur oxides, hydrocarbons, nitrogen oxides, and particulate matter. Ozone and other oxidants resulting from photochemical reactions are common secondary pollutants.(11) Of the pollutants, sulfur oxides have the most pronounced accelerating effect on corrosion. For example, sulfur dioxide will rust iron and attack zinc at relative humidities as low as about 50 percent.(10) As its concentration level is increased, sulfur dioxide will take over a greater portion of the total attack, masking out other contaminants.

Oxides of nitrogen have not been studied as extensively for their influence on corrosion. It is known that a small portion of the oxides of nitrogen, in the presence of water vapor, will form nitric acid. This may react with traces of ammonia and be absorbed by hygroscopic particles which, as discussed below, are corrosive.

High levels of sulfur oxides often are accompanied by high levels of particulate matter.(11) Samples of fine solids taken from contaminated air are found to contain particles of ash unburned fuel, tarry soot, grit, road dusts, incinerator residues, etc. A typical analysis will show organics, sulfates, nitrates, iron, lead, and traces of other metals. The hygroscopic salts present in particulate matter, particularly in the presence of sulfur dioxide, causes accelerated attack on iron, zinc, and other commercial metals.(12) The effect of particulate matter often is minor, when the air is free of pollution.

As will be seen from a study of Table 1, the major source of sulfur dioxide pollution is from the burning of high sulfur coal and oil by power stations and industrial plants. These are the fuels that are least expensive and their continued use has been a matter of public concern for some time. Pollution from the incineration of waste and from the exhaust of internal combustion engines adds to the total, but is of far less importance to the sulfur dioxide level and the resultant effect on corrosion.

TABLE 1. SOURCES IN MILLIONS OF TONS OF SULFUR OXIDES FOR 1965 (13)

Source	Tons x 10^6	Percent
Transportation	0.5	2.2
Industry	8.7	37.8
Electric Power Generation	10.2	44.4
Space Heating	3.4	14.8
Refuse Burning	0.2	0.8
	23.	100.

The amount of man-made pollutants which are emitted into a metropolitan district can be controlled to large extent. However, the dispersion and dilution of such pollutants is more difficult to control, since the natural ventilation provided by wind, etc., is one of the major factors.(14) During a temperature inversion or weather condition resulting in trapped air masses near ground levels, the concentration of pollutant will increase markedly. Usually these periods, which may only occur 1 or 2 percent of the time, are accompanied by high humidity.(15)

Based on general experience, the corrosivity of the atmosphere, where sulfur oxides are the chief contaminant, can be expected to increase several fold in such a period. However, actual data to show the day-to-day correlation of short periods of high pollution levels with the resulting acceleration of corrosion do not appear to be available. Abnormally high rates of metal corrosion at areas just downwind from an emission source have been observed. Here the stack height was insufficient and the diluted flue gas descended down to ground level during stagnant weather periods.

The condensate depositing on metal surfaces such as iron and zinc will be much more acidic than that corresponding to average pollution. The amount of sulfate and other contamination in the rust coat on steel will be increased and tend to affect adversely the corrosion rates during periods when the pollution has again returned to normal levels.

Susceptibility of Metals to Air-Pollution Corrosion

For some metals, particularly steel and zinc, there is a decided increase in the rate of attack when they are exposed to industrially contaminated moist atmospheres as compared with that experienced in rural clean air. The increased tendency to corrosion when the air is polluted can result in a significant reduction in the service life of an external metal structure or system or it can lead to higher costs of maintenance and repair to insure the same performance as the structure would have in an uncontaminated atmosphere.

These considerations were used in the selection of each metal for inclusion in this study. More precisely, the candidate metal must satisfy each of the following conditions:

(1) Air pollution causes the candidate metal to corrode at much higher rates as compared to rural clean air.

(2) The life of a structure or system made out of the candidate metal is significantly shortened by the increased corrosion in polluted air or it requires greatly increased protection and maintenance expense to prevent early corrosion failure of the item in question.

(3) The metal systems or structures, in which the candidate metal is the major component exposed to the atmosphere, has high in-place value.

For some metals, Item 1 is satisfied, namely that the rate of attack is significantly higher. However, the increased attack may not, in some cases, significantly affect the life of the structure or system of which it is a part as required by Item 2. Even when both Items 1 and 2 are satisfied, some of the applications of the metal may not be significant from an economic standpoint.

Copper. An important characteristic of copper and its alloys is its excellent resistance to the atmosphere. Typical corrosion rates are of the order of 1.3 μm/yr (0.05 mpy) in industrial atmospheres as compared with 0.5 μm/yr (0.02 mpy) in rural air.(9,16,16.5) Thus while there is some acceleration in attack resulting from pollution, the higher rate is not significant in a damage sense. The higher attack in polluted air usually results in the more rapid formation of a patina on copper which in turn tends to slow down the attack. Typically, a copper roof or other component outlasts the building or structure of which it forms a part, whether the air is polluted or not.

In summary, one concludes that while the corrosion rate for copper is increased by pollution, and the in-place value in exterior service is high, neither the maintenance cost nor the life is seriously affected in most cases by air pollution. Accordingly, the value of copper components are negligibly sensitive to air pollution. Thus, copper was excluded from the survey.

Lead. Lead is very resistant to atmospheric corrosion whether the atmosphere is polluted or not. In a badly polluted atmosphere the rate of attack may vary from 0.3 to 0.8 μm/yr (0.01 to 0.03 mpy). Rural rates are about 0.3 μm/yr (0.01 mpy).(9) These low corrosion rates are confirmed by experience. Lead roofs installed centuries ago on churches, for example, are still in service. Service life of lead cable, used in overhead telephone distribution, is excellent. Lead was not selected for inclusion in the study because of its excellent resistance to polluted air.

Stainless Steel. The high chromium and chromium-nickel stainless steels are very resistant to atmospheric corrosion. In polluted atmospheres, they may become stained and soiled. However, by cleaning and polishing they can be readily restored to their original luster. Stainless steel architectural components, installed in the early '30s on the Chrysler building in New York are virtually unattacked in spite of the severe industrial pollution in the vicinity. In view of this and other experience, stainless steels were eliminated from the list of candidate metals.

Stainless may be chosen over aluminum because the latter has a tendency to pit in severe industrial atmospheres.

Aluminum. About one-fourth of all the fabricated aluminum produced is used in external applications such as in architectural. In general, aluminum and many of its alloys have excellent resistance to the atmosphere.

If the atmosphere is polluted, the surface becomes covered with dirt and soot and the aluminum tends to become mottled and pitted.(18) In time, the surface will appear roughened although there is no general thinning. After an exposure of seven years in a polluted atmosphere, as depicted in Table 2, pits as deep as 0.35mm(13.8mils) were obtained.(17) Other results show that most of this pitting occurs during the first two years after which maximum penetration increases only slightly. After 20 years' exposure, the depth is similar to that after three years.

TABLE 2. SEVEN YEAR CORROSION RESULTS FOR ALUMINUM ALLOYS EXPOSED TO INDUSTRIAL ATMOSPHERES(17)

Alloy	Corrosion Rate								Depth of Pitting					
	State College(1)		Richmond(2)		Chicago(3)		Widnes(4)		Richmond		Chicago		Widnes	
	μm/yr	mpy	μm/yr	mpy	μm/yr	mpy	μm/yr	mpy	mm	mils	mm	mils	mm	mils
1199	-----	------	0.025	0.001	0.59	0.023	1.22	0.048	0.071	2.8	0.20	7.8	.35	13.8
1135-H14	0.064	0.0025	-----	-----	----	-----	----	-----	-----	---	----	---	---	----
3003-H14	0.071	0.0028	0.48	0.019	1.12	0.044	3.83	0.151	0.094	3.7	0.18	6.9	.26	10.3
3004-H36	-----	------	0.51	0.020	1.37	0.054	2.31	0.091	0.091	3.6	0.12	4.7	.25	9.7
3004-H34	0.066	0.0026	-----	-----	----	-----	----	-----	-----	---	----	---	---	----
5154-H34	-----	------	0.43	0.017	1.40	0.055	2.70	0.106	0.022	8.7	0.24	9.3	.28	10.9
5005-H34	0.064	0.0025	-----	-----	----	-----	----	-----	-----	---	----	---	---	----
6061-T6	0.069	0.0027	0.38	0.015	1.70	0.067	2.62	0.103	0.10	4.1	0.14	5.6	.27	10.6
6063-T6	-----	------	0.25	0.010	1.30	0.051	1.50	0.059	0.13	5.1	0.13	5.3	.28	10.9

(1) Rural atmosphere, (ASTM STP 435, see Bibliography).

(2) Mild industrial. (0.01 ppm SO_2, avg.).

(3) Industrial (0.14 ppm SO_2, avg., RH, 80%).

(4) Severe industrial, Widnes, England.

In rural clean air, the attack is very slight and pitting is negligible. A rural rate of attack as presented in Table 2 is 0.071μm/yr (0.028 mpy) compared to an industrial rate as high as 3.83μm/year (0.15 mpy).

In architectural and in structural applications aluminum alloys, if properly selected, will give years of service in polluted atmospheres. Many examples can be cited, such as the Empire State Building and the Washington Monument, where aluminum is still in service after 30, 40, 50 or more years.

It is concluded that increased corrosion attack due to air pollution is not a significnat factor in the life of externally exposed aluminum(18.5) structures and components. Therefore, pollution costs, based on increased maintenance of aluminum, were not included in this study. However, the effect on air pollution corrosion costs of employing maintenance-free aluminum to replace steel in highly contaminated atmospheres is considered.

Zinc. The corrosion rate of zinc is markedly increased by air pollution. For example, the rate of attack, for 8-year exposure periods, was found to be 1.04μm/yr (0.041 mpy) in rural State College, Pennsylvania, compared to 5.79μm/yr (0.267 mpy) in New York City.(19) Since zinc is not a structural metal coating on steel, the main influence of pollution is to reduce the life of the coating. Galvanized steel sheet with a 2 oz/sq.ft. coating on each face has a 0.0864 mm thick coating (3.4 mils). Theoretically this would last 83 years in State College and 12.7 years in New York. Partly since the coating is not uniform in thickness, rust spots are typically observed in practice at 35 to 50 years in rural atmospheres and 6 to 10 years in severe industrially polluted areas.

Even in industrial areas, with the much shorter life of the coating, galvanized steel is widely used because it is a relatively inexpensive method of obtaining corrosion protection.

Zinc in the form of galvanized steel, has been included in the investigation.

Steel. Steel is used in numerous external structures and systems because of (1) its strength and economy, and (2) its ready availability in a variety of shapes and forms. A large portion of the Nation's external steelwork is exposed to industrially polluted atmospheres. As compared with clean rural air, the corrosion rates in contaminated air are accelerated greatly. At rural State College, Pa., for example, steel in 7-year exposures corroded at 0.013 mm/yr (0.52 mpy), whereas in New York corrosion rates were as high as 0.065 mm/yr (1.60 mpy).(19) These corrosion rates, determined over longer periods of time, will be lowered slightly but not significantly, especially if the residual copper content of the steel is low.

In view of the fact that steel is the major metal of construction for external structures and since it has a propensity for more rapid corrosion when the air is polluted, it was selected for detailed study in this program.

Metal-Protection Practices

Some metals are highly resistant to the atmosphere, whether it is polluted or not. Aluminum and stainless steels develop thin continuous oxide films which confer protection to the underlying metal. Copper and self weathering steels develop corrosion product films which retard further attack.(16) (20)

Ordinary carbon steels, on the other hand, require some form of protection.(21) This can be, a metal coating such as zinc or aluminum(22) (23) (24) which is anodic to the steel, a paint coating, such as an epoxy or vinyl system, an electroplate, such as a chrome-nickel-copper combination, or a rust preventive over a phosphated surface. Many other systems could be mentioned. The most common methods of protection for external structures are hot dipped galvanizing and painting or a combination of both.

Some aluminum alloys are not resistant to the atmosphere, but their corrosion performance may be upgraded by cladding with a layer of pure aluminum or an anodic alloy. Aluminum is sometimes anodized and dyed for esthetic reasons. This also improves its corrosion behavior.

A recent development is electrocoating, which is used on both aluminum and steel. High density, pore-free coats of fluoropolymers or acrylics are available with excellent resistance to the atmosphere.

Air Pollution Corrosion Costs

Air-pollution costs are centered around the extra cost of maintaining a protective coating, which may be paint or zinc, on steel components.(5)(25)(26) In a corrosive atmosphere, the major function of the protective coating is to provide protection although there is some cosmetic benefit as well. However, it is usually not feasible to assign a portion of the extra maintenance cost to this latter factor. Thus the extra painting costs on steel or galvanizing, as a function of air pollution, are most relevant. To avoid either maintenance costs or early replacement resulting from pollution damage, alternate materials resistant to contaminated atmospheres may be employed.

Protection of Steel Surfaces by Painting. Steel surfaces are most commonly protected from the atmosphere, whether it is polluted or not, by applying a suitable paint system. Considerable skill must be exercised in the selection, application and maintenance of an organic protective coating to effectively control corrosion by polluted atmospheres. Because these skills and good corrosion practice are only employed a portion of the time, actual maintenance costs are often higher than need be. For example some companies only paint when they have monies in the budget. At this time costs may be greater than if painted earlier because of the additional amount of surface preparation required to remove corrosion products. In addition early failure may result from the use of low cost paints having less protective power. All these factors give rise to aggravated costs, however, they can be credited to pollution since they might not have occurred if pollutants had not been present.

High quality paint formulations are required to obtain satisfactory protection of steel structures exposed to badly polluted atmospheres.(21,27,29) Some measure of the aggressiveness of the atmosphere can be obtained by noting the behavior of bare steel, whose corrosion rate, as discussed elsewhere, largely is a function of the moisture, sulfur dioxide and particulate matter present.(28) Similarly, the life of a paint coating on steel is adversely affected by these environmental conditions. In addition, ozone, oxides of nitrogen, and solar radiation tend to promote weathering of the paint film.

There are two common mechanisms by which the life of a paint film is shortened in polluted air. One is the local corrosion at holidays in the paint film. The adjacent painted steel can serve as the local cathode and attack and undercutting of the paint is accelerated at the holiday. A similar mechanism involves ion transport through the paint film, and subsequent rusting at the paint-to-steel interface. A major effort in the development of protective paints for steel surfaces exposed to atmospheric pollution is concerned with delaying the onset and spread of this underfilm attack.(29.5) The second form of paint failure results from the weathering of the exposed paint surface and its soiling by particulate matter.

Unlike the rusting of steel, which can be expressed quantitatively in terms of metal loss or depth of attack, there is no precise method of recording paint failure.(30) The appearance of rust streaks, blisters, cracks, or crazing, loss of the top coating and loss of color or surface character are all examples of criteria now used. From a maintenance standpoint, the appearance of rust streaks, underfilm attack, or the loss of the top coat is a sign that repainting is in order. Where maintenance is delayed, excessive resurfacing costs are required.

The annual cost of corrosion protection of a steel system by paint is greater when the atmosphere is polluted. There are several approaches to the problem of arriving at the difference between this cost and that of pollution-free, or clean rural air. Procedures given consideration for use in this investigation are enumerated below:

(1) Establish the original cost of painting a steel structure or system and convert it to an annual cost, using the corresponding paint life, in years, for (2) rural and (b) polluted conditions, respecitvely. The difference between these two figures is the annual cost to be charged to pollution.

(2) Calculate the cost of painting and repainting the steel structure to provide underfilm corrosion protection for its normal life span in (a) rural and (b) polluted atmospheres. The difference, converted to an annual cost, is charged to pollution.

(3) Establish the cost of increasing the thickness of the original paint sufficiently to delay underfilm attack in the polluted atmosphere equivalent to that experienced with a nominal paint film in rural air. This extra cost divided by the life in years will be charged to pollution.

(4) Compare the cost of maintaining a protective paint system on aluminum and on steel in a polluted atmosphere. The difference in the two annual costs can be ascribed to the control of underfilm corrosion of steel by air pollution.

The first procedure has merit and is a practical method of comparing costs in clean and polluted atmospheres. It was not chosen since it is more usual to repaint and maintain a system or structure to avoid early failure where the atmosphere is polluted.

The third procedure assumes that the thickness of the paint is the only factor in the failure of the steel surface. Actually the initial preparation of the steel surface, prior to painting, also is an important factor in the tendency for steel to corrode more rapidly at the paint-to-metal interface where there is pollution. Accordingly, this method is considered only partially applicable.

There is some merit in the fourth method, namely comparing the effectiveness of the same system applied to steel and to aluminum. However the data required to apply this procedure do not appear to be available.

The second method was chosen for the purposes of this investigation. The comparison of maintenance painting costs in clean and polluted air is in accord with procedures employed in the real world of engineering. This follows from the fact that the useful economic lifetime of external structures has been established on the basis of other criteria such as amortization for business, tax, financing, and other purposes. To avoid the problems involved in premature failure of such investments as are caused by pollution, maintenance procedures are established to insure normal life.

In some cases maintenance cannot be provided. For this situation, the replacement costs involved in early failure in polluted air were compared with the expense involved under clean rural conditions, each computed on an annual basis.

In order to arrive at the extra annual maintenance expense caused by pollution, as outlined in the second procedure it was necessary to follow a series of steps.

First, the total amount of each item in use was established. Second, this amount in tons or other units was converted into exposed surface area. Third, the portion of this total area exposed to polluted air was estimated. Fourth, the annual extra cost of protection by paint, per unit area, was calculated for each system. Fifth, the area (3) and annual cost figure (4) were combined to obtain the total loss for each item to the Nation.

It is possible to estimate from past shipment records the total units and/or weight of any particular system presently in use, the procedures used in these calculations are described in Appendix A. Sometimes the total amount of the system in use was available in the number of units or could be derived from the total capacity, as in the case of tanks. In most cases, the amount in use was expressed in tons.

For each type of structure the thickness range of the steel used in typical designs was established.(21)(30,5) Knowing the thickness, one can convert tons to area. For steel plate as used in tanks, or for sheet in roofing and siding, the exposed area on one side only is used. For structural steel, as in bridges, the total surface area is used.

Each system was considered separately, in arriving at an estimate. The typical manner in which the system was employed also was taken into consideration. For example, above ground external storage tanks in petroleum service are invariably exposed to polluted air. On the other hand, power transmission towers are mostly in rural areas and only a small portion are exposed to pollution.

The total cost of applying a paint system to a steel surface can be estimated by combining the cost of surface preparation, materials, and labor. A large number of paint references were searched, but there were only a few which reported actual costs. The range of values found for high quality metal protective paints are given in Table 3, Part A. Some of these have been taken from recent sources and are not too different from current costs. During the last decade, even with more frequent use of labor-saving procedures, the main portion of the expense that has increased is labor. The cost of protective paint systems has not increased markedly, and some systems such as epoxies are actually lower in cost than when they were first marketed some years ago.

The paint cost selected for making the calculations are presented in Table 3, Part B. The original painting usually is higher in cost because it includes surface preparation, such as blast cleaning. For most systems, the first cost was taken as \$0.50/sq ft and the repaint cost at \$0.40 sq ft. While such a high quality system will protect steel for 12 years in rural air, the life in polluted air will vary with the application. Elevated water tanks, on the average, are not exposed to the highest level of pollution. For a good quality coating, 8 years is taken as typical. In petroleum service, tanks are normally exposed to a high level of pollution and the life may be shortened to 5 years. In chemical and other industrial service, a higher quality coating job is usually specified than in the petroleum field. The choice of \$0.62 per sq. ft. reflects this difference. Bridges are more costly to paint than other types of structures and

TABLE 3. PAINT COSTS FOR PROTECTING STEEL (21,26,31,32,33,34)

A. Range of Published Values

Description	Range of Cost Dollars/Square Foot
Sand blasting	0.10 to 0.20
Primer	0.09 to 0.18
Top coat, each	0.11 to 0.21
Complete coating - 4 to 6 mils	0.30 to 0.75

B. Application Costs in Dollars Per Square Foot Chosen for Structural Steel and Metal Work

			Life Years	
System	Original	Repaint	Rural	Polluted
Water Tanks	0.50	0.40	12	8
Petroleum Tanks	0.50	0.40	12	5
Chemical, etc. Tanks	0.62	0.46	15	7
Bridges	0.65	0.65	15	8
Outdoor Metal Work	0.50	0.40	12	8
Power Transformers	0.50	0.40	12	8
Outdoor Lighting Fixtures	0.50	0.40	12	8

repainting is not always done at the most favorable time. Thus considerable surface preparation and spot priming is necessary. In view of this, the repaint cost is taken as equal to the original.

The annual extra cost per unit area to be charged to air pollution is calculated in the following manner. First the typical useful life of the structure is established through the use of the IRS table. Next the cost of providing paint protection for this period of time under rural conditions is computed. Similarly the higher cost required for the same life period under polluted conditions is computed. The difference between these two costs is converted, to an annual basis by dividing the normal life of the structure. These factors, reported in dollars per quare foot per year, are shown in Table 4.

Protection of Steel Surfaces by Galvanizing. Galvanized steel structures and galvanized roofing and siding often are painted to extend the life in polluted atmospheres. The extra costs charged to air pollution can be developed in a manner similar to that already described for painted steel. Some examples are given in Table 4.

Some types of galvanized steel components are normally not maintained by painting. For example, galvanized fencing is usually replaced. Wire rope and cable, after the zinc coating is gone, rapidly loses strengh as a result of the steel corrosion. In other words, its useful life has been shortened by pollution and it also must be replaced. Similarly pole-line hardware in polluted areas tends to fail earlier than the wooden pole itself. This involves an extra replacement cost that is not experienced in rural environments.

TABLE 4. ANNUAL EXTRA PAINTING COST FOR PROTECTING STEEL EXPOSED TO POLLUTED ATMOSPHERE

Steel System	Life in Years					Level of Pollution		Paint Cost $/Sq.Ft.			Extra Annual Maintenance, Cost in $/Sq.Ft./Yr.	
	System	Paint Clean	Paint Polluted	Zinc Coating Clean	Zinc Coating Polluted	Degree	Range in ppm of Avg. SO_2 (35, 39)	Clean	Polluted	Difference	Steel*	Galvanized*
Tanks												
Water	50	12	8			Average	.03-.06	1.77	2.60	.83	0.0167**	
Petroleum	11	12	5			High	.08-.18	.46	.98	.52	0.0473	
Chemical	11	15	7			High	.08-.12	.45	.88	.43	0.0391	
Bridges	30	15	8			Average	.03-.06	1.30	2.64	1.34	0.0447	
Power Transformers	30	12	8			Average	.03-.06	1.10	1.60	.50	0.0167**	
Street Lighting	20	12	8			Average	.03-.06	.77	1.10	.33	0.0167**	
Outdoor Metal Work												
Doors and Frames	45											
Window Sash, Frame	45	12	6			High	.08-.12	1.60	3.10	1.50	0.0333	
Structural Steel	45	12	8			Average	.03-.06	1.60	2.35	.75	0.0167**	
Roofing, Siding	45											
Galvanized Roofing (A)	45	15	7	35	10	High	.08-.12	.34	2.10	1.76		0.0392
and Siding (B)	45	15	10	35	15	Average	.03-.08	.34	1.30	.96		0.0213
Coil Coated Steel												
Coated Galv. Steel												
Transmission Towers	30	--	10	35	15	Average	.03-.06	----	.70	.70		0.0233
Pole Line Hardware	30	--	10	35	15	Average	.03-.06	----	.70	.70		0.0233
Chain-Link Fence	20	--	6	20	8	Average	.03-.12	----	.1074	.1074		0.0054
Chain-Link Posts	30	--	10	35	15	Average	.03-.12	----	.70	.70		0.0233

* Difference on extra cost above rural divided by system life.

** These factors differ by only ±$0.0001, so all were made equal.

For those cases where painting was employed to extend the life of a galvanized structure, the same procedures were used as those described for painted steel. However, it was assumed that the first painting was not required until the rust started to appear at weathered spots in the zinc coating.

In the case of wire rope, the cost of corrosion damage by pollution was established by dividing the cost of the wire rope by the years of service in polluted and in clean air respectively. The difference in the annual cost for polluted environments compared with that for rural service was charged to pollution.

For pole-line hardware, the usual practice is to regalvanize the items and return them to service. This procedure was made the basis for the calculation. In general where there are variations in the application of the basic method, these are explained in the individual sections where the specific system is discussed.

COMPONENT-SYSTEM SELECTION

Up to this point, considerations have centered on the behavior of metal surfaces, protected and unprotected, as exposed to outdoor air environments. It shifts now to the systems, subsystems and components in which metal surfaces appear.

According to the evaluation formula, the cost to society of deterioration of a surface depends on the value of the system in which it appears and the number of such systems serving under outdoor, polluted corrosive environments. At one extreme, such as the outside surface of a gasoline can, the cost of surface deterioration is effectively negligible. It is a low-value surface, the corrosion of which does not diminish either the utility of the container, nor its expected life.

At the other extreme, such as a contact point in an electrical device, the cost of surface deterioration is effectively great. It is a high-value surface, the corrosion of which compromises the utility of the device, invokes maintenance costs, and shortens the assessed life of the device. Between these extremes are numerous systems, subsystems, and components of greater or lesser values linked to the integrity of contained metal surfaces; and that integrity linked to their corrosion proneness to air pollutants.

The problem therefore is to identify important surfaces, to place value on them, and limit the quantification of corrosion loss to only the important, high-value ones. Placing an accurate value on surfaces, according to the foregoing examples and formulae, would require a tenuous evaluation process that considers (a) the surface's function, (b) its location on a component, (c) the intrinsic value of the component and its effect on the economic operation of the system it is in, and (d) the total value of the systems in operation in the Nation at the time in question. Because there is no such evaluation process in existence to our knowledge, the value of surfaces have to be qualitatively estimated and compared by inferences drawn from published data on hard systems, published primarily by the Census of Manufactures.

Hard systems originate under two broad census categories; Division C--contract construction, and Division D--manufacturing. Cities are the product of contract construction where pollution is mainly concentrated and where most manufactured products (components and systems) reside. Other divisions in the SIC network employ systems originating in Divisions C and D, and represent service environments for them. That is, all divisions, agriculture, mining, transportation, etc., all use systems originating in Divisions C and D--so do Divisions C and D, for that matter. The point is that component/system definition is found only in statistics for construction and manufacturing.

Component/Systems Framework

Cities contain two broad categories of constructed structural systems, infrastructure and to coin a term, "economic structures". Both are built by the contract construction industry. "Infrastructure" includes general construction for transportation and communications, power facilities and other public-service buildings, and capital equipment. "Economic structure" is here defined as containing all evident buildings used by industry, commerce and households. All elements of infrastructure and economic structure comprise the real estate of the city; Division C of the SIC anatomy.

In, on and around the real estate of a city resides manufactured products or systems; Division D of the SIC anatomy. Thus, there are three varieties of systems of concern in this study, related to the city, the statistics and each other as matrixed in Table 5.

TABLE 5. INTERRELATIONSHIP OR ELEMENTS OF A CITY

	Economic Structure	Infrastructure
Division C - Contract Construction	A. Building Construction	B. General Construction
Division D - Manufacturing	C. Manufactured Products	C. Manufactured Products

All constructional and many manufactured systems are exposed to some extent to air pollution. More specifically, some of the components comprising constructional and manufactured systems are more constantly exposed than others. Therefore, it is the component level that is meaningful, and where surfaces begin to become identified, along with their exposure, service behavior and their maintenance requirements.

Building construction and general construction breakdown into eight system elements as shown in Table 6. Manufactured systems components, as produced by manufacturing industries, are given by SIC 25, 33, 34, 35, 36, 37, 38, 39. All reside on and around the two types of construction as capital equipment. Although it is possible to be quite specific in ranking these products, according to value of volume produced, and tonnage of metal consumed, their distribution into capital equipment by industry is specific, in only a relatively few cases in the SIC data breakdowns.

At this point, there appears to be two separate somewhat independent areas of concern, each to be reduced to sufficient specificity to apply the value assessment equations. However, skipstepping ahead and taking advantage of hindsight, it turns out that the most important systems and components in the Division D--manufacturing areas--were related to construction systems. The manufactured items unrelated to construction systems turned out to be relatively small-volume; or in service in protected environments where air pollution is absent, such as steel furniture (SIC 25) and computers (SIC 36); or in service in aggressive environments where air pollution is the least damaging environmental element, such as automobiles on salted roads (SIC 37), and chemical equipment (SIC 35). Many more examples can be cited.

Thus, the two major areas become more and more related, as the manufactured products winnow down to essentially building components. Accordingly,

TABLE 6. SYSTEM ELEMENTS OF CONSTRUCTION

Building Construction

(1) Residential Building

- Single family
- Multifamily
- Other

(2) Institutional Building

- Religious
- Educational
- Hospital
- Social and recreation

(2) Industrial

- Chemical plants
- Metallurgical plants
- Food processing plants, etc., (SIC major groups 19-39)

(4) Commercial

- Offices
- Warehouses
- Stores
- Restaurants
- Garages

General Construction

(5) Transportation Structures

- Railroads
- Highways
- Bridges
- Overpasses

(6) Utilities

- Electric power
- Gas
- Telephone and telegraph
- Water

(7) Public Airports

(8) Military Construction

Note: Military construction is not exactly infrastructure, but is related in the sense that it provides a public service, i.e., defense.

a better matrix representation is as indicated in Table 7. Each cell represents a component/system combination. For example, (a) steel tanks in a chemical installation, (b) roof siding and drainage in single family dwellings, (c) power distribution transformers in electric power utilities, etc.

For practical reasons that after all gives dimension to the problem, census data is not neatly kept in terms of all of these cells. For large-item components, it is. But for most, the cells are in effect grouped; in many cases, it is left to the investigator to deduce breakdowns of component consumption by system, an intellectual exercise that all too often, for lack of reasonable access or precision information, degenerates into meaningless speculation.

For these reasons the later computations on corrosion loss are oriented around components, with the service environment of the various systems coming in to establish technical judgments on the probable corrosion behavior of component surfaces accordingly. The details of the procedure for deferring systems and components is described in Appendix B.

TABLE 7. INTERRELATION BETWEEN BUILDING SYSTEMS AND COMPONENTS

Components → Construction Systems	Steel Storage Tanks	Structural Steel for Bridges	Steel Transmission Towers	Structural Steel for Buildings	Steel Fence	Pole Line Hardware	Outdoor Lighting Equipment	Power Distribution Transformers	Roof Siding Drainag	Prefab Metal Bldgs.	Metal Doors, Windows
Industrialized Installations											
26 Paper											
28 Chemicals	(a)										
29 Petroleum											
30 Rubber											
33 Primary metals											
34 Fabricated metals											
35 Machinery, excluding electrical											
36 Electrical machinery											
37 Transportation equipment											
Other Installations											
Single family room									(b)		
Multifamily											
Commercial office buildings											
Commercial warehouses											
Railroad yards											
Highways											
Bridges											
Overpasses											
Utilities											
Electrical Power								(c)			
Gas											
Telephone and telegraph											
Water											
Airports											
Military Construction											

CONTEMPORARY AIR-POLLUTION COSTS, 1960-1970

Contemporary air pollution corrosion costs concern existing component-systems in outdoor use during the decade of the sixities, under generally prevailing air pollution conditions of that time; it ignores regional, and/or neighborhood perturbations, as discussed elsewhere. Some of the local variations in air pollution would tend to increase the corrosion damage substantially and thus have an effect on the total cost of air pollution. The arbitrary constraints of the study made it necessary to deal strictly in national averages. The following evaluation procedure was used to reach the air pollution corrosion costs of the foregoing nine systems.

Evaluation Procedures

In the economic assessment, the corrosion cost of air pollution divides into two terms. The first is the extra cost of maintenance, mainly painting. The second is the cost of shortened appraisal life of systems, due to evidence of pollution, i.e., excessive painting or replacement of components in evidence at the time of appraisal.

Marginal Maintenance Costs

The marginal maintenance cost over a system lifetime is equivalent to the extra painting costs necessitated by the presence of air pollution as compared with that experienced in clean, rural air. Other reasons for extra painting, such as marring, are excluded. Because the painting cost is proportional to the exposed area, an input estimate of the total exposed metal area is computed for components attached to pollution-vulnerable systems. The extra annual cost of repainting this area is calculated for the economic life of the system exposed to air polltuion.

The annual census statistics on components, (standard industrial classification), are recorded in either numbers of units shipped, or in total weight shipped. These data are converted into equivalent exposed area by computations that vary with the component considered. Straightforwardly, for example, the typical dimensions for transformer cases of various size capacities are found in design references. Numbers of units shipped by size capacity are found in Census data. To determine total area, by average unit, it is necessary to calculate the area of average units in each size range, and multiply by the number of such units shipped. Perhaps the least straightforward, however, is to compute that area for, say, pole-line hardware, which is reported as "tonnage shipped" and comes in a polyglot of sizes and shapes. Most other components, however fall somewhere in between these extremes. Nevertheless, the best reasonable estimates possible were made to convert census data into total area.

These total areas are for all systems exposed to all kinds of air throughout the country. They accordingly relate to an average frequency of painting. Where pollution imposes a greater than-average repainting frequency, the extra cost of painting over a system's lifetime, as a function of air-pollution density, is computed.

Shortened-Lifetime Costs

The average economic lifetimes of all kinds of systems are given by the depreciation guidelines and rules, procedure 62-21 of the Internal Revenuse Service for average service, including average air pollution conditions in the U.S. When considering individual assessments, assessors use these guidelines, primarily as a point of departure. For example, the guidelines give galvanized steel fences an average economic lifetime of 30 years. Upon assessing a fence of some given age in a rural area, an assessor would probably find little or no corrosion and fewer-than-expected coats of paint. He accordingly would allow less depreciation by the formula.

$$\text{Assessed Value} = 1 - \frac{\text{Service Age}}{\text{Economic Lifetime}} \times \text{initial cost.}$$

Oppositely, if he sees an overcorroded or excessively repainted fence for its age, he will accord it a less-than-average lifetime, using a lower-than-average value in economic lifetime, in the formula and accordingly computing a lower assessed value.

Because the annual census statistics on components are recorded in value shipped it is a straightforward computation to integrate in-place value of shipped components over the "guideline" lifetime of the component.

Depreciated value is half of that, and yearly depreciation rate is 100% ÷ years lifetime.

As the assessor lowers the economic lifetime of the system as a function of pollution damage, the higher the depreciation rate. In a given year, that margin applied to the total in-place value of the component in a region (assessed on per capita) computes that year's value loss due to pollution damage.

The integrated in-place value of a component was computed from data points for as many years as the Census Department has reported figures during the years of component lifetime. In-between points were straight-line interpolations; and outside points, straight-line extrapolations.

Alternate Materials

The extra expense and inconvenience of maintaining steel construction or systems in polluted atmospheres can be avoided by substituting an alternate, maintenance-free, pollution-resistant material of construction. In the typical case, this substitution involves a higher cost of installation than for the equivalent in steel. This premium, divided by the life of the system in years, can be taken as an annual charge to pollution. A more rigorous analysis is to take the annual expense involved in installing and maintaining a steel and a substitute material system, respectively, in polluted air, and to compare these costs with those for rural conditions, using as reference the annual cost of either painted or galvanized steel, whichever is the most appropriate. For the alternate material, the extra annual cost in polluted air above that for steel in clean air would be a charge to pollution. The saving, if any, by the use of the alternate material instead of steel can be established by comparing the annual extra corrosion cost due to pollution for each material.

Evaluation of Surviving Steel Component Systems

The component systems that survived the final screening are listed in Table 8. In most cases the tonnage shipped each year was high in the SIC list. Other cases, where the rank was not so high, were included because of the high potential economic loss for corrosion damage by air pollution. A good example is chain-link fence which is typically used in urban areas where it is attacked by polluted atmospheres.

Each of the nine component systems were analyzed individually. The order of presentation is determined not by the economic importance, but by the similarity of the calculation. For example, systems involving galvanized steel were grouped together at the end of the list. Under "Outdoor Metal Work" an assortment of external structures and components were combined for calculation purposes.

For each of the steel systems, the calculations and the sources of information used will be found in the corresponding tables in Appendix C.

TABLE 8. COMPONENT SYSTEMS WHICH SURVIVED FINAL SCREENING AND WERE SELECTED FOR DETAILED STUDY

SIC Code	System Description	Metal Rank	Portion of Metal Content Subject to Atmospheric Corrosion	Potential Economic Loss vs. Air Pollution Corrosion Damage
34-435-9	Steel Storage Tanks Fabricated from Plate	7	large	high
34412	Highway and Railroad Bridges of Structural Steel	15	most all	high
36122	Power Transformers	38	small	medium
36425	Street Lighting Fixtures	35	most all	medium
	Outdoor Metal Work			
34411	Structural Steel for Buildings	5	small	high
34392	Prefabricated Buildings		large	high
34492	Portable Buildings		large	high
34441-11	Roofing and Siding		large	high
34441-16	Industrial Siding		large	high
34460 34421,2	Outdoor Gratings, Grills Fire Escapes, Metal Doors, Window Sash		large	high
34413	Power Line Transformers Towers of Galvanized Steel	9	all	medium
36441	Pole-Line Hardware	28	all	high
33156 34816	Chain Link Fencing and Steel Gates	33	most all	high
33151	Galvanized Wire Rope	30	large	high

Steel Storage Tanks

Steel storage tanks are used for water, petroleum products, various chemicals, etc., in liquid and gaseous form. Certain food products, detergents, and industrial raw materials are stored in powdered form in tanks. The bulk of the storage tanks are externally mounted in regions where the atmosphere is polluted.

Economic Importance. It is estimated that the tonnage of steel plate in steel storage tanks of all types is 13,800,000 with a depreciated value, based on original shipping cost, of $23,289 billion for the Nation. The procedures for establishing these figures from SIC statistics is given in Appendix B. From these figures and from other evidence, storage tanks are found to be an important part of the total external steel work.

Control of Corrosion. Storage tanks exposed externally and above ground usually are protected from atmospheric corrosion by painting. Sometimes it is necessary to paint them more frequently than for other types of structures. Water tanks, for example, are subject to severe condensation particularly in the spring when humid air comes into contact with steel chilled below the dew point, by the cold water in the tank. Bulk storage tanks, containing other liquids, also show the effects of the precipitation of dew. In the season when pollution is high, this condensation is acidic and increases the rate of deterioration of the paint as well as rusting under the paint.

Assessment of Losses. External steel storage tanks were divided into three categories each being treated separately; namely, (1) elevated water storage tanks, (2) bulk storage petroleum tanks, and (3) chemical and industrial storage tanks (chemical, rubber, paper and pulp, etc.). The calculations for each category are shown in Table C-1 in Appendix C.

Water Tanks. A one million gallon elevated water tank (1 MG) is a typical size for an urban community. From a reference listing, all the water facilities for communities of 25,000 population and over(40), it was estimated that the total elevated steel tank storage capacity for the Nation was equivalent to 11,000 typical sized 1 MG tanks. A second estimate, as explained in Table C-1, was based on the total tonnage of steel in place. These calculations indicated that the total number of typically sized tanks was about 14,300. The average of the two estimates is 12,700. The annual extra cost of maintenance painting for 1MG water tanks is calculated to be $288/year. Since some water tanks are located upwind from the pollution sources in the typical metropolitan district, the total exposed to average pollution was considered to be about 80 percent. Combining these factors, results in an annual loss of $3,400,000.

Petroleum Tanks. The total bulk storage capacity of the petroleum industry, according to the American Petroleum Institute figures for 1962, is 17,981,306,000 gallons. If one projects this to 1970, using growth in refining capacity as a guide, one finds that the Nation now has 20,000,000,000 gallons or 477,000,000 barrels storage capacity.

On the basis of discussion with engineers familiar with refinery operations, it was established that bulk storage tanks are typically 100,000 barrels. Oil companies use smaller tanks, such as 10,000 barrels at distribution depots. Approximately 2/3 of the total storage was judged to be at the refinery and the rest are largely at the distribution centers.

Calculations for petroleum product tanks are presented in Table C-1. On a volume basis, allowing 10 percent for ullage, there are 3,465 large and 17,325 small tanks. The corresponding areas are found to be 31,450 and 6,530 square feet, respectively. Based on the fact that pollution is relatively high in the vicinity of petroleum product tanks, maintenance factor derived in Table C-1 is relatively high namely $0.0473/sq.ft./yr. The annual corrosion loss for the total of the two tank sizes is estimated to be $10,520,000. On a tonnage basis, the loss is $11,100,000. Averaging the two results gives an estimated annual loss of $10,810,000.

Chemical and Industrial Tanks. External storage tanks used for industrial products in gas, liquid, or powdered form are usually subjected to air pollution. Paint maintenance costs tend to be higher, than say for water tanks. Appraisers use an 11-year life for steel tanks in chemical and related industries. Tank life often will be determined by internal corrosion, in many cases, rather than by external attack resulting from air pollution. Nevertheless, the external tank must be protected for the duration of its normal service.

There are some 4,830,000 tons of such industrial tanks in use. The extra cost of maintaining a protective coating on industrial type tanks is about 0.0391 sq.ft./yr. A typical area factor for plate going into steel storage tanks is 200 square feet/ton. If one considers that 85 percent of the tonnage in use is in polluted air, then the annual loss arising from the extra cost of painting is found to be $32,100,000. These calculations also are given in Table C-1, Appendix C.

These tanks are in such diversified service that no statistical data were found that would enable an alternative route for readily checking the magnitude of this loss. No doubt each of the major industries could be surveyed and their totals combined.

Summary of Annual Tank Losses. The total extra annual corrosion loss charged to pollution for externally mounted steel storage tanks exposed to air pollution is summarized below:

Elevated Water Storage	$ 3,400,000
Petroleum Product Storage	$10,810,000
Chemical and Industrial Tanks	$32,100,000
Total	$46,310,000

Highway and Railroad Bridges

Most of the Nation's important bridges are made of steel. A bridge is defined by highway engineers as a crossing with a span of 20 feet or more.

Economic Importance. Structural steel bridges are high in dollar value. It is estimated by the Federal Highway Administration that there are 563,000 highway bridges in use. Some 236,000 are in the Federal-Aid Highway Systems. In addition, there are some 94,000 railroad bridges. By comparing road mileage figures for the Nation for rural, municipal, state, and federal roads, and by making certain assumptions, it is estimated that about 30 percent of the total bridges are in metropolitan areas. This estimate may be compared with that suggested by Erickson and Morgan of the U.S. Bureau of Public Roads. They estimated in 1955 that 25 percent of the bridges are in urban locations.(21)

Using the Department of Commerce statistics for 1963, the estimated total tonnage of structural steel for bridges currently in use, based on a 30-year average life is 18,134,000 tons for the Nation. The total value of the steel, as shipped, is estimated to be $\$4,093 \times 10^6$. Applying the 30 percent estimate to these figures gives 5,450,000 tons and $\$1,230 \times 10^6$ respectively.

Factors Determining Life of Bridges. Although appraisers use 30 years, the actual life of a bridge is more often between 50 and 100 years. Corrosion damage is the main reason for reducing the load limit of a bridge before it is finally replaced. There are two sources of corrosion damage for bridges located in metropolitan areas. One is corrosion of the superstructure by polluted air, and the other is damage to the bridge deck by salt. In northern cities where deicing salt is used in winter months, bridge deck and guard rail damage is fairly common. At marine locations, ocean spray may be conveyed by the wind to a highway or railroad coastal bridge and cause both deck and superstructure damage.

The steel bridge structure, especially older designs, has many vulnerable sites where corrosion damage can arise when the air is polluted. Girders tend to show corrosion around rivet or bolt heads and at contact surfaces where moisture may enter between flange plates at bearings and at connections. Cracks may show up at welds or at a sudden change in section where there are stress concentrations.

Steel decks must be covered to prevent salt damage. Seals must be provided over expansion joints to keep out salt, and foreign matter. Corrosion damaged decks are seldom the controlling factor for determining the useful life of bridges in polluted atmospheres because they can be repaired and replaced. A rough deck, however, adds to the impact load from traffic.

The weakened elements are usually in the superstructure where loss of section by excessive corrosion in polluted air or the development of cracks has reduced the load limit.

Control of Corrosion. The most common method of controlling the corrosion of steel bridges is by paint coatings. As with other painted steel structures, the life of the coating depends on two factors: (a) the underfilm attack and (b) the weathering of the paint itself. Much research has been carried out to control underfilm attack. Moisture will in time penetrate the paint film and cause, in the case of steel, underfilm rusting.

Bridges occasionally are protected by galvanizing the steel before erection. If galvanized steel is used, it eventually has to be painted.

To properly maintain a bridge the paint system employed should be specially selected for the environment. It is recognized that the corrosivity caused by air pollution may be higher at one end of a large bridge than at the other. The paint system should be chosen to meet the worst condition one expects in service.

Since the labor cost of application may be as much as ten times the cost of the paint materials, it does pay, in most situations to use the best available coating for the particular environment. Paints which can resist the acidity developed when moisture deposits on the surface in a sulfur contaminated atmosphere may cost more than those satisfactory in rural clean air.

The life of a good quality paint system on steel in rural clean air may be from 10 to 15 years. In urban polluted air, the life may be 5 to 8 years on highway bridges.

Assessment of Losses. Both the first cost of the original paint system and the maintenance of the coating during the life of the bridge will be higher in an industrial atmosphere than for a similar bridge in rural clean air. The calculation of the maintenance factor, $0.0447 sq.ft./year shown in Table 4 is based on the higher costs shown in Table 3 for bridges, than for other external structures and for lifetimes of 15 and 8 years, respectively.

The calculations for assessing the extra cost of maintaining bridges in polluted areas is depicted in Table C-2, Appendix C. The calculations as previously discussed are based on a conservative estimate that 30 percent of the bridges are in polluted areas. From the total of 18,134,000 tons in use, an area factor of 125, and a maintenance factor of $0.0447/sq.ft./year, the annual loss is estimated to be $30,400,000.

Power Transformers

The bulk of the power transformers are boldly exposed to the atmosphere. Transformers mounted in underground chambers lose capacity during hot weather, because of overheating. For this reason, transformers in underground distribution areas are also mounted above ground where conditions permit. The sizes range from 15 KVA units on power poles to massive units of 10,000 KVA or larger in substations and at power plants.

Economic Importance. Power transformers have a high inventory value, namely $12,316 x 10^6. However, only a small percentage of this value is for the external housing. The bulk of the installed value of the steel is for the silicon core. Maintenance of the housing, however, is essential to protect this big investment. From personal observation, externally mounted power transformers are known to be a significant portion of the externally exposed steel of most communities.

Control of Corrosion. Paint is the normal method of protecting the external surfaces of power transformers from the atmosphere. Utilities tend to favor lead suboxide paint formulations for this application. Whether the air is polluted, or not, good results usually are obtained in this service.

Assessment of Pollution Costs. By combining information obtained from a study of the design of various sized transformers, with statistics giving the number of each size shipped each year, it was possible to develop an estimate of the total area of the housings for all the different sized transformers in service. The maintenance factor of $0.0167 sq.ft. for transformers was developed as shown in Table 4, and is based on service experience with average pollution. The calculations are based on 80 percent of the installed area of 556,630,000 square feet being exposed to pollution and indicate that the total extra cost of annual maintenance if $7,450,000. Additional details are given in Table C-3 of Appendix C.

Street Lighting Fixtures

Outdoor steel lighting fixtures are most commonly installed in populated districts. Many are now being made of aluminum and require very little maintenance. Poles are often made of wood, aluminum, reinforced concrete, or fiber reinforced plastic instead of steel to reduce maintenance costs. A discussion of the advantages of using maintenance-free materials in polluted areas is presented elsewhere.

Economic Importance. Although the total tonnage of steel in lighting fixtures can be estimated from available statistics, the dollar value assigned these fixtures is much greater since it includes the value of the electrical fittings but excludes the lamps. The inventory value of $1,221,438,000 does not represent the mill cost of the steel components. Lighting fixtures were included since the tonnage in service was significant, namely 984,574 and since most of the steel used is light gauge and thus the area factor will be large.

Control of Corrosion. Lighting fixtures made of steel are protected by galvanizing or aluminizing. Some fixtures are painted for esthetic value. Painting is the most common form of repairing damaged surfaces and fixtures that already have seen years of service are maintained by painting.

Assessment of Corrosion Losses. Most of the Nation's lighting fixtures are in heavily populated areas. About 85 percent of the tonnage going into light fixtures is estimated to be exposed to air pollution. In some designs part of the metal is enclosed or buried and not subject to atmospheric corrosion.

For lighting fixtures, the maintenance factor of $0.0167 sq.ft./year was taken from Table 4. This extra cost is for maintaining external metal work by painting in an environment with average air pollution. Using 20 percent of the total tonnage and an area factor of 400 sq.ft./ton, it can be shown that the annual losses for light poles if $1,110,000. Similarly for the fixtures, the annual cost is $10,800,000 giving a total of $11,910,000. The details of these calculations together with footnotes concerning the values selected are presented in Table C-4, Appendix C.

Outdoor Steel Metal Work

Under this heading, a variety of external steel items have been grouped. This includes roofing, siding, downspouting, portable and prefabricated buildings, outdoor grillwork and fire escapes, metal doors (e.g., garage-type) in residential, commercial and industrial buildings, window sash and frames, and structural steel. Total tonnage in service figures have been developed for each of these items.

Most of the items have large areas of externally exposed surface per ton of installed metal. The one exception is structural steel. In commercial applications only a small percentage of the structural steel is externally exposed. In existing construction, structural steelwork is enclosed for the most part.

Economic Importance. From the data developed from the national metal statistics on outdoor steel work of a variety of types, it is estimated that 26.6×10^6 tons are exposed to industrial environments. Large tonnages are also exposed to other urban environments. These tonnage figures and the fact that much of the steel is light gauge with a much higher area factor than the material going into, say, bridges or tanks, indicate the total losses will be extremely high for this category.

Control of Corrosion. Some of the items listed above are protected by galvanizing, others are protected by aluminizing. The most common method of controlling the attack is to provide a good coating of a resistant paint. Painting can be delayed where there is a zinc or other metal coating on the steel, until weathering has progressed to where rust is just starting to appear.

Economic Assessment of Losses. Each item, for which a tonnage-in-use figure was developed was considered separately for purposes of calculating losses. For example, the total tonnage of galvanized steel roofing, siding, and roof drainage such as gutters and downspouting is estimated to be 17,200,000 tons. About 20 percent of this tonnage is used in rural applications leaving 13,750,000 tons. As outlined in Table C-5, Appendix C, part of this latter tonnage, namely 5,500,000 is in industrial, part in commercial, namely 2,060,000 and the rest is in residential service and not included. Tonnages also were developed for galvanized prefabricated and portable steel buildings. Combining these tonnages for (a) industrial and (b) commercial environments, gives 10,335,000 and 4,820,000 tons respectively. Since the material used in industrial environments is 22 galvanized sheet gauge, an area factor of 1400 sq.ft./ton was used (one side). For commercial service, an area factor of 2500 corresponds to 28 sheet gauge. The extra maintenance cost figures of 0.0392 and 0.0213 per ft^2/yr are taken from Table 4. The calculation shows $567,000,000 for industrial and $257,000,000 for commercial atmospheres, resulting in a total cost of $824,000,000/year.

To this figure must be added the cost of painted steelwork (not galvanized) in polluted atmospheres. These calculations are also presented in Table C-5, Appendix C. Where the exposure is industrial, a maintenance factor of $0.0333/sq.ft./year was employed and for commercial exposures, $0.0167/sq.ft./year. In the case of window sash an area factor of only 100 sq.ft. per ton was used, since only part of the steel is exposed. The maintenance factor of $0.06/sq.ft./year is high mostly because of the extra labor cost involved in preparing and painting metal sash and frames.

For the last item, it was estimated that 15 percent of the industrial tonnage and 15 percent of the commercial tonnage is in external use. On the other hand, it was considered that 65 percent of the steelwork in utility service is external, in view of the practice of externally mounting most of the power plant except office space, repair shop and control room.

In summary, the total annual extra cost involved in outdoor metal work is assessed at $914,015,000. For a list of the items that make up this total, refer to the end of Table C-5, Appendix C.

Pole Line Hardware

Galvanized steel is the most common material of construction for overhead pole line hardware. Clevises, eye nuts, J-bolts, rope clips, and insulator caps are made of copper-bearing forged steel. Some items such as strain clamp bodies, hooks, and sockets are made of galvanized malleable iron. These can be lumped with the steel for purposes of estimating pollution costs. The main factor in pole line hardware, is the shortened life of the zinc coating in industrially polluted air. This necessitates its replacement or repair before the wooden pole itself requires replacing. In rural air, pole-life determines the time when the pole and the attached hardware is to be replaced. Creosoted wooden poles typically last 20 to 25 years in either rural or urban exposures.

Economic Importance. Although the amount of pole-line hardware per pole is not very significant, the total number of poles is in the hundred millions. Many metropolitan areas use poles extensively in all but the civic center itself for the overhead distribution of power and telephone services. Since the bulk of the hardware is galvanized steel or galvanized iron, and since this hardware must be replaced at least once during the life of the pole in industrial regions, the cost that can be charged to air pollution is a significant part of the total cost for the Nation.

Corrosion Control. For pole line hardware, the main reliance for corrosion protection is upon the zinc coating. Usually two ounces per square foot is specified. Utilities prefer to remove corroded hardware, which, if still serviceable, is sent to a local galvanizer for reprocessing. Painting of corroded hardware in situ does not seem to be widely practiced.

The ideal hardware should last at least as long as the pole. Under rural conditions, this aim is achieved easily. On the other hand, pole hardware in industrial locations tends to fail in 15 years or less. Thus, it must be replaced before the deterioration of the pole itself requires replacement of the whole installation.

Assessing Pollution Costs. Two sources of metal data are available for pole line hardware. The first estimate is based on steel statistics. The total amount of pole line hardware and related products is 4,062,735 tons. It is estimated that 75 percent, or 3,040,000 tons is pole-line hardware. By combining the area factor of 450 square feet per ton with an estimated average area per pole of 2 square feet, one finds there are 342×10^6 poles.

The second estimate is based on the consumption of zinc for pole line hardware. It is estimated, from the amount of zinc slabs going into baths being used for pole-line hardware, that there are 82,500 tons of zinc coating in use for this purpose. A bath efficiency of 50 percent was assumed. Each pole uses 8 oz. of zinc (4 sq.ft. x 2 oz./sq.ft.). This figure, combined with the zinc tonnage figure results in 330×10^6 poles. Averaging the two computations gives 336×10^6 poles.

For service in polluted air, pole-line hardware must be replaced once during the lifetime of the pole. The charge against pollution then is the cost of replacing this hardware, see Table C-6, Appendix C. Since it is common to regalvanize pole-line hardware and return it to service, this cost, taken at \$0.55 per square foot combined with a labor cost of \$25 per pole, results in an annual extra cost of \$1.20/pole, based on a pole life of 22.5 years. It was estimated that 40 percent of the poles are exposed to polluted air. Combining these figures with the 336 x 10^6 poles gives a total of \$161,000,000/year.

Chain Link Fencing

One of the most common metallic structures found in metropolitan areas is chain-link fence. Nearly all industrial plants use some fencing. Most of the chain-link fencing in existence today is galvanized. Plastic coated and aluminized chain-link fence are being used, but represent only a few percent of the total installed. Aluminum chain-link fencing also is available.

All the metal that goes into a chain-link fence is exposed to the atmosphere. A wire gauge size of nine (0.148 inch diameter) is most commonly used for chain-link fence because of the economy involved. This size is heavier than required for security or for corrosion. If one specifies an even heavier gauge, the extra material as expected raises the cost of the product. On the other hand, by specifying a lighter gauge wire, the higher wire drawing costs more than offsets the savings in material.

Economic Importance. The amount of chain-link fence in predominantly industrial service is 4,018,980 tons. In addition, some 6,028,471 tons of posts and fittings are employed to support this fence. The total inventory value is \$1,444,013,000. On the basis of these data it is evident that chain-link fencing is one of the more important systems involved in accessing corrosion damage caused by air pollution.

Control of Corrosion. The zinc coating on galvanized fencing is typically 1.25 oz./ft^2. It may last about 20 years in rural air and 8 years more or less in industrial air. Corrosion control, as with other galvanized surfaces, sometimes involves painting. To obtain a life equivalent to that in rural air, chain-link fence will require several paintings. More often, chain-link fencing is replaced. It is most common to paint the posts and replace the wire.

Assessment of Losses. Chain-link fence comes in heights varying from 36 to 144 inch. For the computation, a 72-inch high fence is chosen as typical. All computations in Table C-7 of Appendix C are based on a 100-foot length of fence as a unit. (Contractors commonly use this size for estimating, then make adjustments for other sizes.)

The weight of 100 feet of fence, 6 feet high is calculated to be 415 pounds, which compares well with an estimate of 400 pounds received from a fence supplier. By taking the total tonnage of chain-link fence in service of 4,018,980 tons, it can be shown this is equivalent to 19.35 x 10^6 100-foot lengths, six feet high. Since about 80 percent of such fence is in industrial and urban service, the total 100-foot lengths exposed to pollution is about 15.5 x 10^6 100-foot lengths.

For rural conditions, 20 years for the fence and 30 years for the posts is a typical life. For polluted atmospheres, a paint coating is required after 8 and 14 years to obtain the same life as in clear air. This extra cost, as shown in Table C-7, Appendix C, amounts to $0.0054 per square foot per year based on the area of the fence, and not on the surface area of the wire itself. A maintenance cost of $0.0233 per square foot per year is used for the galvanized posts, based on a 15-year life for the original galvanized coating.

If 25 percent of the owners maintain fencing by painting, the extra annual cost is shown to be $20,400,000. If another 25 percent replace the entire fencing after allowing it to rust for a few years beyond failure of the zinc the extra cost per year, above equivalent rural costs on this basis comes to $38,000,000. This calculation is based on an installation cost of $440 per 100 feet of chain link fence. The rural life was 20 years plus 10 years rusty and the industrial life was 8 years plus 2 years rusty for the original and for each of two replacements. The most common method of maintaining fence in industrial environments is to replace the wire only and maintain the posts by painting. The remaining half of the owners, using this basis for calculation experience on extra annual cost of $13.65 per 100 feet length of 6-foot high fence as shown by the calculations in Table C-7. This results in a loss to the Nation of $106,000,000.

A summary of the annual total extra cost for galvanized steel chain link fencing is provided at the end of Table C-7. The grand total for chain-link fencing is $165,800,000.

Galvanized Wire Rope and Cable

There are many external uses for wire rope and cable. Overhead lead telephone cables are supported by galvanized steel messenger wire. Guy wires are used extensively to brace wooden telephone poles. Traffic lights and signs are often hung from galvanized steel wire cables. It is estimated that 40 percent of the wire in use is exposed to polluted atmospheres.

Economic Importance. The total weight of galvanized steel rope and cable shipped each year is of the order of 200,000 tons. The individual strand of galvanized wire itself has a mill price of about \$221 a ton including \$40 a ton premium for the zinc coating. The forming of galvanized wire into rope increases the cost about three times. The inventory value, as shipped, of the galvanized wire rope now in service is estimated to be \$2,007,500,000.

Corrosion Control. The zinc coating, which typically is thinner on wire than on sheet, usually will provide protection by isolating the steel surface from the atmosphere. Once the zinc has weathered away to where steel is beginning to be exposed, the remaining zinc will provide sacrificial protection to the adjacent steel surface. Once the zinc is gone, the corrosion attack is accelerated, the wire loses strength and requires replacing.

In rural clean air, wire rope may last typically about 20 years whereas in industrial atmospheres, wire rope may lose its coating in 5 to 8 years. While the heaviest coatings obtainable should be used in industrial atmosphere on sheet, this is not practical on wire because of flaking in service. However, in practice, there is considerable loss of zinc.

Assessment of Corrosion Losses. From steel statistics, it is estimated that there are 6,301,000 tons in service at a shipped value of \$4,015,000,000. The average cost per ton is about \$635. By comparing the rural life cost per year with that in industrial atmosphere one obtains a figure of \$47.7/ton/year for the extra cost of wire shipped to replace wire corroded by air pollution. On the basis that 40 percent of the total tonnage estimated to be in use is exposed to polluted air, the total loss is calculated to be \$120,000,000/year, as shown in Table C-8, Appendix C.

From zinc statistics, the total tons of slab zinc consumed each year to galvanize wire is known. Since galvanized wire lasts from 5 to 20 years or more in the atmosphere, an average life of 15 years was used to obtain an estimate of the total tons of zinc coating on the steel wire in service. The total zinc consumed in wire baths is equal to 572,213 tons since 1955. The typical zinc bath has an overall efficiency of around 50 percent. Some zinc is lost and some wire receives more zinc than the minimum required for the grade.

For the calculation, a typical wire size was chosen, namely 0.120 inch diamter. Seven strands of this wire are used on 3/8 inch wire rope, a very commonly used size. A thousand feet of 0.120 inch wire size after double galvanizing has 26.6 oz. of zinc (0.85 oz./sq.ft.). When made into 3/8 inch 7-strand rope this becomes 186 oz. of zinc/1,000 feet. If one assumes all the wire rope in existence was made into this size, one can show that there will be 49.3×10^6 lengths of 1,000 foot 3/8-inch wire cable.

The alternate computation also depicted in Table C-8 is based on the replacement cost of 1000 foot lengths of 3/8-inch stranded wire, and using the same expected life in rural and industrial life as before. The results show a total for the Nation of $103,500,000 per year. This is a reasonably close estimate and was arrived at independently of the steel data above. Averaging the two values gives an annual loss of $111,800,000.

As originally anticipated, the cost of the damage to wire rope resulting from air pollution is high. This cost does not take into consideration the expense of shipping, installation, and replacement. These charges, if they could be established and included, would increase greatly the amount charged to air pollution.

Power Line Transmission Towers

Approximately 98% of the power transmission towers in service today are constructued from galvanized structural steel.(41.5) This material also is used for radio and TV transmitter towers, telephone microwave systems, and for flood lighting towers (e.g., in sports fields, industrial plants or rail yards).

For service in industrially polluted areas, there is some interest in alternate materials which are maintenance free. In the late 50's, structural aluminum alloys were introduced. Their corrosion resistance to polluted atmospheres is excellent. More recently self weathering steels have been tried for power line transmission towers. Because of the higher strength, less low alloy steel is required in the structure than when carbon steel is used. Since the corrosion rate is about one-fifth that of carbon steel, only a small corrosion allowance, if any, is needed. If the dark rust coat is not acceptable from an esthetic standpoint, the structure may be painted. Service experience has shown that paint coatings are more durable on self weathering steels than on carbon steel because any rust that forms at breaks or holidays is less voluminous and there is less rupturing of the paint film.

For suitably chosen aluminum alloys, or for boldly exposed self weathering steels, maintenance is practically eliminated and no significant losses can be ascribed to air pollution. For galvanized steel structures, on the other hand, polluted air sharply reduces the life of the zinc coating and the protective paint system that must be applied after the zinc has weathered to expose the steel base.

Economic Importance. Power line transmission towers and similar structures used for other purposes have high in-place value and are also high in the amount of exposed area per total weight of metal. The present inventory value is estimated at $1,165,000,000. Only about 12.5 percent of the towers in existence are in polluted areas.(42.5)

Control of Corrosion. The heavy zinc coating usually provided on structural steel intended for tower use will provide excellent protection in rural atmospheres. For control of corrosion after the zinc has weathered to the point where the steel is just becoming exposed, a paint system usually is applied. In rural atmospheres, this point is reached between 25 and 40 years, whereas in industrial and in commercial regions, the life of the zinc coating is shortened severely to 5 to 15 years.

Assessment of Corrosion Costs. Although it is usual to expect greater than the assessor's life for a transmission tower of 50 years, for the purposes of this investigation, this value is used. It is well established that both the zinc coating on galvanized steel and the subsequent paint coating that must be used to protect the steel base after the zinc has failed both have a shorter life in industrially polluted air. A paint system that gives 15 years' protection over weathered zinc in rural air may only give 6 to 10 years' service in polluted air. The computation is based on a 15-year life in rural and an 8-year life in polluted air.

Actual costs for painting transmission towers vary with the size and location of the tower. The range is $375 to $1000. It is considered more costly to paint in an urban area, since air pollution increases the cleaning and application cost. On the other had, transport of painters and equipment to a rural site can add to the cost, especially when the line is not readily accessible by road.

A typical tower weights 7.5 tons and has a surface area of about 2500 square feet. The total weight of galvanized structural steel employed in towers is estimated to be 1,449,000 tons. Since a typical tower weighs 7.5 tons, it can be calculated that there are about 194,000 "average" towers in use. This number may be compared with the results of a survey of 40 utilities conducted in 1963. A total of 124,020 towers and substation structures were found in their systems.(54) About 12.5 percent were located in contaminated air.

Of the 194,000 towers in use, using the same 12.5 percent. only 24,300 are exposed to pollution. Using the typical area for a tower of 2500 sq.ft. and the maintenance factor developed in Table 4, the annual loss as shown in Table C-9, Appendix C, becomes $1,480,000.

Air Pollution Damage Costs for Alternate Materials

Pollution can be considered a benefit, in the sense that it tends to promote the use of more resistant materials in place of steel for some systems. This, in turn, often results in a saving to the economy in the form of reduced wastage of materials and increased reliability. An assessment has been made of the cost of corrosion control using selected alternate materials in polluted environments as compared with the cost of painted steel or galvanized steel. Several metals were considered in this analysis, namely self weathering steel, aluminum, and copper.

Roofing Metals

An analysis of the corrosion economies involved in well known roofing metals is presented in Table C-11, Appendix C. In polluted air, such as is typically experienced in industrial areas, galvanized steel roofing may last 10 years or less before rust appears and paint maintenance is required to save the remainder of the investment. Aluminum will last at least 50 years without maintenance. Copper will last well beyond 100 years. Terne plate, even with the heaviest lead-tin alloy coating available for roofing, namely 0.5 oz. per square foot, must be painted at the time of installation. In this condition, it will last 50 years, although repainting in this period may be desirable for esthetic reasons.

The gauge (special galvanized sheet gauge) for galvanized steel chosen for the study is 22, which is heavier than typical for the roofing in general use. However, for industrial service, a heavier sheet normally is preferred. Aluminum is usually about 33 percent thicker for the same service than its equivalent in steel. In the present example, 18 gauge (Brown & Sharp) aluminum is chosen for the comparison. Both galvanized steel and aluminum are commonly corrugated to increase stiffness and strength. Copper and terne plate are used in thin gauges, and 28 and 26, respectively, were chosen for the comparison. Each of these two materials requires extra support and these costs are included in Table C-11. Mill sheet prices were used for the comparison.

A galvanized roof when compared on an equivalent installed basis, is about 2.5 times as heavy as aluminum. It must be overlapped somewhat more than aluminum. A higher labor cost applies to the heavier galvanized steel than for the aluminum. For copper and terne plate, there are extra installation steps, such as soldering or crimping of seams which is not required with aluminum.

The installed charged as listed in Table C-11 rate copper as the highest and galvanized steel the least expensive. However, the cost per year in polluted air is lowest for copper and highest for galvanized steel.

If one uses the galvanized steel roofing cost in polluted air per year as the basis of reference, it is found that the savings if alternate materials were used would amount to 73.5 percent for aluminum, 77.5 percent for copper, and 61.3 percent for terne plate. If this basis were used as the amount to be charged to pollution, and if all the galvanized roofing were replaced, the annual pollution charges would be reduced from $824 million for galvanized to $218 with aluminum, or $202 million for copper or $326 for terne plate.

If, on the other hand, one uses as a reference the annual cost of galvanized steel roofing in rural clean air and compares this expense with that for each of the four materials in polluted air, one finds that for copper and aluminum, the annual costs are less, even in polluted air, than that for galvanized steel in clean air. As shown in Table C-11, the aluminum roofing on this basis costs $0.001/sq.ft./year less and the copper roofing $0.003/sq.ft./year less than rural galvanizing. Thus for these two materials, it is concluded there is no charge to air pollution. For terne plate in polluted service, the cost above rural galvanized is $0.005/sq.ft./year. This may be compared with the cost of galvanized steel of $0.035/sq.ft./year on the same basis.

About 25,000 tons of terne plate go into roofing each year. Almost all of this is for residences and institutions. The actual tonnage used in industrial and commercial applications is not known, but probably is less than 1,000 tons a year. If one considers that as much as 50,000 tons of terne plate roofing are currently exposed to contaminated atmospheres, the annual cost, with an area factor of 3,000 would be about $750,000 per year.

In view of the lack of data and the small size of the estimated annual loss, terne plate was not included in the overall assessment of annual losses.

Aluminum Siding, 1969

Most of the aluminum siding goes into residential and mobile homes. Industrial consumption is not reported by the Department of Commerce nor by the Aluminum Association. The latter, however, have privately indicated their estimate for 1969, namely a total of 53,000,000 pounds of aluminum went into industrial siding.(42)

The calculations shown in Table C-12 in Appendix C have made use of this statistic. A popular thickness for industrial siding is 20 gauge or 0.032 inch thick. This weighs 55 pounds per 100 square feet. An installed cost for the aluminum siding is calculated to be $0.59/sq.ft. versus $0.43/sq.ft. for the equivalent size in galvanized, 0.275-inch thick.

The 53,000,000 pounds of aluminum, if all of 20 gauge, would have an area of 96×10^6 sq/ft. Item 5 in Table C-12 shows the installed cost for this amount of aluminum to be $56,700,000 compared with galvanized steel of $41,300,000. The premium paid above galvanized steel, for this area of aluminum siding is $15,400,000. This amounts to $308,000 per year over the 50-year life. If the production figures for other years were available, one could estimate the tonnage in use and then calculate the total annual premium to be charged to pollution.

A more rigorous comparison is to use the annual cost of galvanized steel in rural conditions as the reference in establishing the annual loss to pollution. The calculations, as listed in Item 6 of Table C-12 shows the annual cost of 96×10^6 sq.ft. of siding to be $1,133,000 for aluminum versus $1,180,000 for galvanized in rural air. Since there is no essential difference in these estimates, it is concluded that there is no charge to pollution for the use of aluminum siding in industrial areas on this basis. (For this same area, as might be expected, the annual charge to pollution for galvanized steel is almost \$3 million; see Item 7 in Table C-12).

Self Weathering Steel

The cost of self weathering steel is about 40 to 45 percent higher, on a weight basis, than carbon steel. These steels are bought on strength and other physical properties and not on composition. Atmospheric corrosion rates in polluted air are typically 1/4 to 1/6 that of carbon steel.(20)

On an installed basis, there are two factors which reduce the cost-differential between these steels and carbon steels. First little or no corrosion allowance is required, and second the higher strength often will permit a reduction in the totalweight required for the design in typical cases. Installation costs tend to run some 10 percent higher because of the higher skills required for fabrication.

Schmitt and Mathay(43) provide cost data for comparing carbon steel with self weathering steel. Their data forms the basis for the calculations recorded in Table C-13 in Appendix C. A comparison is made on the basis of substituting bare self weathering steel for painted carbon steel in bridge construction.

The installed cost, as shown in Item 2 of the table, is \$371 for carbon steel versus \$445 for self weathering steel. Since about 10 percent less weathering steel would be used than for an equivalent structure in carbon steel, this last figure is reduced to \$403 per ton. On this basis, as shown in Item 3 of the table, the annual premium, corresponding to a bridge life of 30 years, would be \$1.07/ton of carbon steel replaced. This premium, in a sense, could be charged as an annual cost to pollution. However, if one used the costs for painted carbon steel in rural clean air as the basis for establishing the extra annual pollution cost, one finds that instead of a loss, there is a net saving of \$4.33/ton/year in the use of self weathering steel in polluted air; see Items 4 and 5 in Table C-13. In view of this situation, no annual cost to pollution was charged to the use of self weathering steel.

As a matter of interest, additional comparisons were made between painted carbon steel and self weathering steel. For example, if one calculates the expense of maintaining an average carbon steel bridge in a polluted atmosphere, the annual cost is \$11.00/ton. As shown by Items 6 and 7 in the table, the substitution of self weathering steel results in an annual saving of \$9.93/ton.

It also has been determined, that if the self weathering steel is painted, and one allows a 25 percent longer life in polluted air for the protective coating than the same coating on steel, there is no essential difference in the annual cost between the two systems. The real savings come, as one might expect, by designing the bridge or structure to use bare self weathering steel.

Stainless Steels

Most of the AISI 200 and 300 series of stainless steels have excellent resistance to polluted atmopsheres. Although the material cost is 5 to 9 times that of carbon steel, no corrosion allowance is needed and the maintenance cost is negligible. Although no calculations were made, the cost of pollution analysis would be very similar to copper. Compared to the cost of painted steel in rural atmospheres, the annual cost for stainless steel in polluted atmospheres would be less. No charge was made to air pollution for the use of stainless steel as an alternate material.

Summation of Annual Extra Corrosion Losses Caused by Air Pollution

Nine major classifications of external metal structures have been analyzed in the assessment of corrosion damage caused by pollution. These systems are listed in Table 9, together with the estimated annual corrosion loss in dollars. The total loss, for the Nation, was found to be \$1.45 billion.

For painted steel structures, the annual loss was based on the extra maintenance expense required to insure normal system life. The extra maintenance expense per unit beyond clean air costs were applied to the total area of surface exposed to pollution. For galvanized steel, several procedures were used. For roofing and siding, the extra cost of maintenance painting, after the zinc coating failed, to obtain normal system life was compared with similar costs pertaining to clean air environments. This method also was used to compute part of the costs for chain link fencing. For fencing, 75 percent of the calulation was based on the costs of replacement. For galvanized pole-line hardware and for galvanized wire rope, the extra cost of replacement, based on shorter service life in polluted air was converted to an annual basis, and used as the cost.

In the study of alternate materials, particularly aluminum, copper, and self weathering steel, the annual premium above carbon steel paid for these materials was compared with the annual corrosion cost of galvanized or painted steel in rural clean air. In most instances, the use of these alternate materials in polluted air cost less per year than steel in clean air. In view of this situation, no charges against pollution were made for alternate materials.

TABLE 9. SUMMATION OF ANNUAL EXTRA LOSSES DUE TO CORROSION DAMAGE BY AIR POLLUTION TO EXTERNAL METAL STRUCTURES FOR 1970

Steel System or Structure	Basis for Calculation	Annual Loss in $1000	For Calculation See Table
Steel Storage Tanks	extra cost of maintenance	$ 46,310	C-1
Highway and Rail Bridges	extra cost of maintenance	30,400	C-2
Power Transformers	extra cost of maintenance	7,450	C-3
Street Lighting Fixtures	extra cost of maintenance	11,910	C-4
Outdoor Metal Work	extra cost of maintenance	914,015	C-5
Pole-Line Hardware	extra cost of replacement	161,000	C-6
Chain Link Fencing	extra cost of maintenance and cost of replacement	165,800	C-7
Galvanized Wire and Rope	extra cost of replacement	111,800	C-8
Transmission Towers	extra cost of maintenance	1,480	C-9
		$1,450,165	

ANALYSES OF COST OF CORROSION DAMAGE BY AIR POLLUTION, 1970 to 1980

The total cost of corrosion damage to the Nation ten years hence will be affected by changes in the corrosivity of the atmosphere and by the total amount of external metal structures susceptible to attack. The effects of changes in population, density of population in metropolitan districts, energy production, industrial activity, control of corrosion technology, labor cost of maintenance, and level of pollution regulation must be examined and the individual and combined trends with time estimated.

Economic Trends

Power generation and industrial activity are affected by economic growth. One of the variables, for which records are available, is population growth. A recent report indicates the total population for USA in 1970 to be about 204 million.(44) As shown in Figure 1 this is expected to be about 227 million in 1980 corresponding to a growth of 11 percent. The metropolitan areas are expected to accommodate most of this growth and increase at an average of 12 percent. By 1980, it is expected that 80 percent of the population will be crowded into metropolitan districts occupying 1.5 percent of the land.

The population growth, together with a higher standard of living for a greater portion of the population, is expected to increase the demand for energy and also for products and services. Energy production is increasing at the rate of 7 to 8 percent each year, and is predicted to increase by 78 percent in 1980.(46) The various sectors which determine industry growth, judging from the recent past, probably will not increase uniformly. Iron and steel production has increased 26 percent during the past decade. Another example is the chemical industry which recently has been increasing

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10 X 10 to the inch.

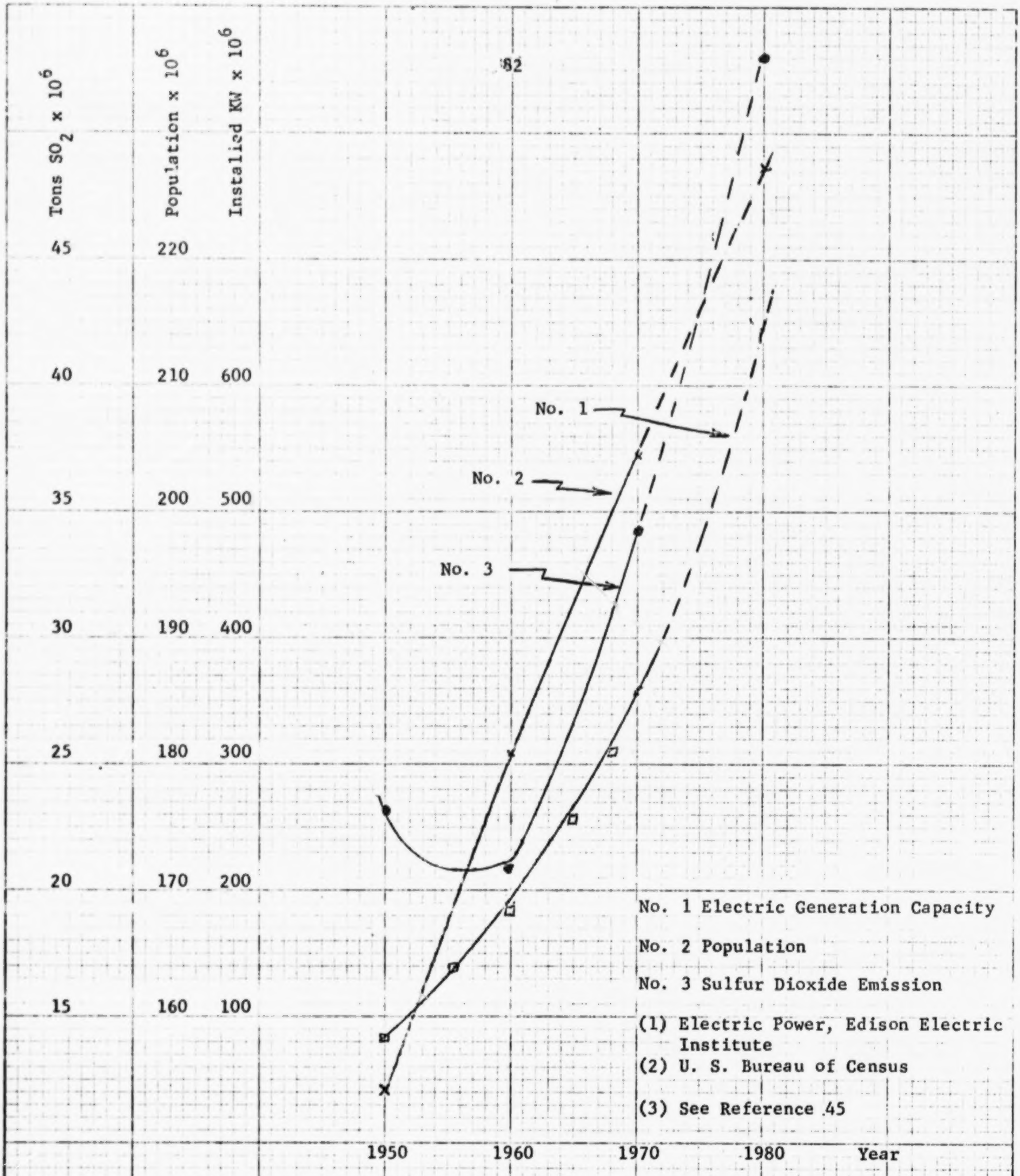

FIGURE 1. PROJECTED GROWTH IN POPULATION AND IN POWER GENERATION AND INCREASE IN SULFUR DIOXIDE EMISSIONS WITH NO RESULATION.

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at 8.6 percent per annum. Plastic production is growing at a phenominal rate and will double in the next five or six years. However, the overall growth of all industry is conservatively estimated to be about 4 percent per year or roughly 48 percent by 1980.(47)

Changes in the Amount of External Structures

The increase in industrial activity can be expected to result in an increase in some types of external structures. Storage tanks will increase in total capacity as a result of the expansion in the chemical, petroleum, and other such industries. Highway bridges and overpasses will increase in number with the growth of the highway system needed to accommodate the 11 percent increase in population. On the other hand, railroad bridges and other such structures may not increase in number, since no major expansion of the rail system is anticipated.

Power and telephone distribution is showing a tendency to go underground in at least a few of the most modern suburban developments. However, the high expense involved, and the great demand for low cost homes in these new areas, probably will delay the general acceptance of this technique for many years. Only a very small portion of the low and the high voltage transmission networks will be underground by 1980.

Security measures around public and private buildings will be intensified. Thus, the use of chain-link fencing, street lighting, storefront protective grill work, special metal doors and gates, can be expected to increase markedly in the next ten years. Security measures also may necessitate moving some types of external structures underground, where they are less vulnerable to damage.

Also expected to increase with growth in population and the trend to multi-family dwellings are metal roof-top facilities, such as air conditioning, water storage, ventilation and external fire escapes.

The total of the new external carbon steel structures will probably be of the order of 30 percent. This does not seem unreasonable when one considers the growth trend for structural steel and plate shown in Figure 2. It is predicted that 80 percent of the existing structures will still be in use in 1980. Thus about 20 percent of the new carbon steel structures represent replacement, leaving only 10 percent net growth in carbon steel structures. The total amount of all new external structures probably will increase by 30 percent, of which 20 percent will be made of materials not subject to corrosion damage by air pollution.

Increased Use of Alternate Materials

The ever increasing cost of maintaining steel systems in polluted areas is a major reason for considering alternate, maintenance-free materials. The expense for recoating a steel structure involves the cost of the paint which has not altered greatly in the past ten years, and the cost of the labor for its application. In the last decade, the hourly wage has increased about 2.5 times and if one includes the overhead expense, the increase is about 3 times. For example, Cincinnati contractors are currently charging about \$12 an hour (with overhead) as compared to about \$4 an hour ten years ago.(50) The projected increase would be about \$20 per hour by 1980, which is a greater increase than the predicted growth in the economy.

Thus maintenance-free materials, in spite of their higher cost in typical situations, are becoming more attractive with time. In fact, avoiding the cost and inconvenience of maintenance, whether the environment is polluted or not, is the most important reason for choosing alternate materials instead of steel. In addition, there often are design economies, lower labor costs for installation, and esthetic considerations that may play a role in the ultimate choice of a candidate material.

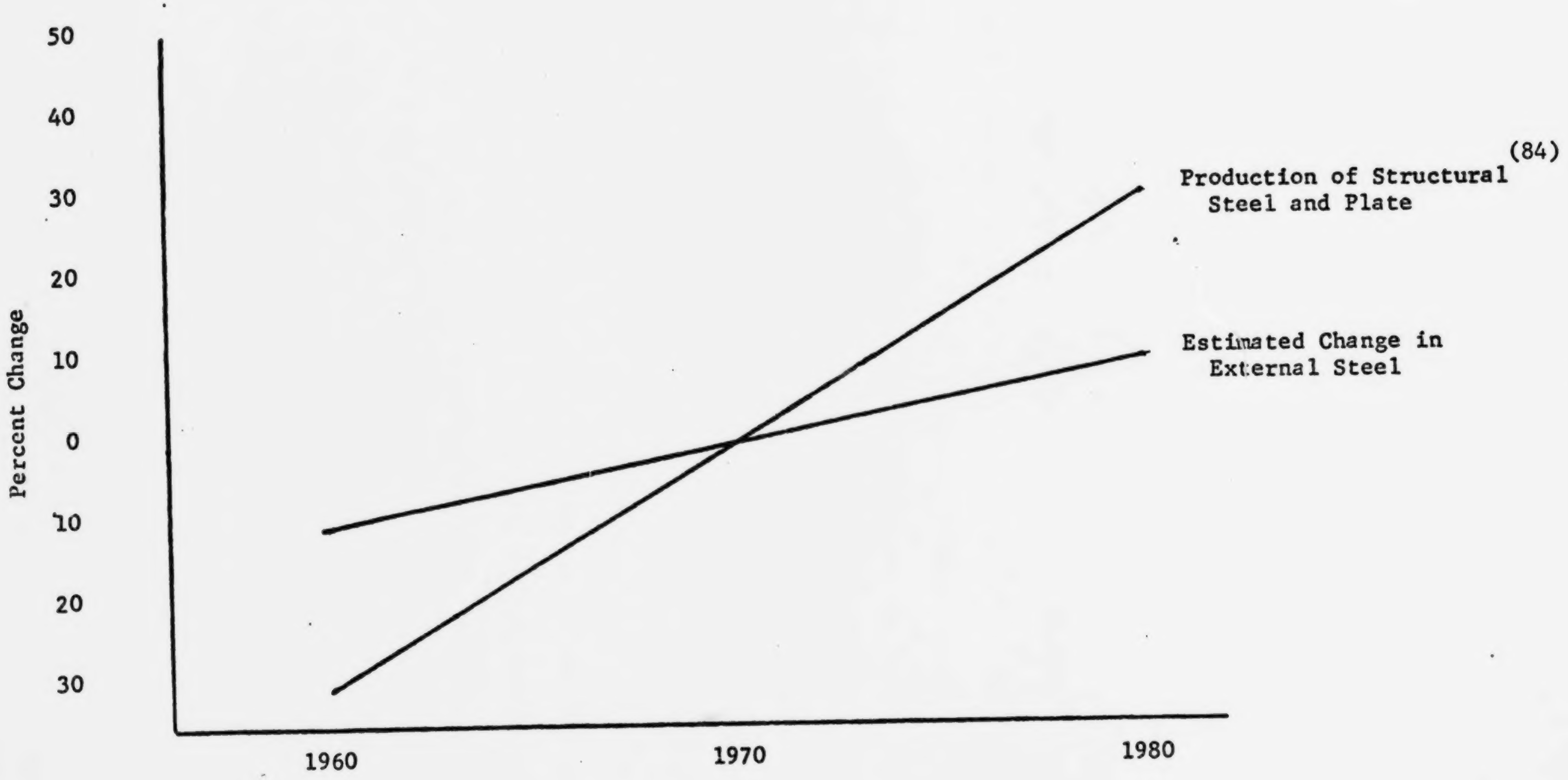


FIGURE 2. GROWTH OF STRUCTURAL STEEL AND PLATE PRODUCTION AND ESTIMATED TOTAL CHANGE IN EXTERNAL STEEL EXPRESSED AS PERCENT.

For structural steel applications and for galvanized sheet, both aluminum and self weathering steel are strong contenders as alternate materials and should find much wider application by 1980. Statistical data allowing one to predict growth trends for industrial and commercial applications of these materials do not appear to exist. For aluminum, the amount of sheet products used in all forms of construction have increased during the 60's from 0.58 to 1.18 billion pounds or over 100 percent. Aluminum siding for residential service has grown at an even faster rate of 225 percent during the past decade. In 1969, aluminum siding for industrial use was 53 million pounds, or 15.5 percent of the residential market. This application will probably double or triple by 1980.

Statistics were not found for self weathering steels and from a discussion with a steel company representative one gained the impression that only a few percent of the total structural steel production is of this grade. However, the metals maintenance-free characteristics have become widely known and the trend to its use in external structures such as bridges and other exterior structures is expanding. It can be expected to capture a greater portion of the market by 1980.

Aluminum coated steel sheet and fiber reinforced plastics are currently increasing in their use and probably will acquire a higher percentage of the market for painted and galvanized steel by 1980.

Alternate materials are being offered in new combinations to reduce the price and increase the ease of installation. Roofing is now available in thin aluminum or copper sheet bonded to plywood panels. To compete with such products precoated galvanized roofing is being offered for service in polluted areas.

For siding, coil coated steel or aluminum is now available for exterior use with 15 to 20-year warrantee. By 1980, the net result of the use of all such newer materials will be to lower or eliminate maintenance costs that can be charged to pollution.

Changes in Corrosivity of the Atmosphere

The two major factors affecting the corrosivity of the atmosphere to steel, and to the protective coatings used to retard or control the attack on steel are (a) the level and type of pollution and (b) the amount of moisture.

Atmospheric pollution by fuels containing sulfur is the most important factor in determining its corrosivity to steel. The predicted potential emission of sulfur dioxide into the atmosphere from all sources is shown in Figure 1. This prediction, indicating a 55 percent increase in the discharge of SO_2 into the atmosphere by 1980, does not take into account the steps, now underway, to find practical methods of reducing the emissions from the burning of high sulfur coal and oil.

Switching to low sulfur fuels will make an immediate improvement in the level of sulfur dioxide in a high pollution area. Unfortunately the supply of low sulfur fuels close to the regions where they are most needed are limited. Shipping costs combined with high demand has resulted in a several-fold increase in the cost of these desirable fuels in typical areas.

The use of low sulfur fuels may only be necessary during periods of limited ventilation. Power plants, for example, according to recent studies only make a major contribution to the sulfur dioxide level during certain stagnant weather periods such as temperature inversions. By the use of low sulfur fuels during these periods, which may be only 1 or 2 percent of the time, much of the contamination from the large users of fossil fuels can be avoided. The regulation of the space heating-type smaller plants is much more difficult.

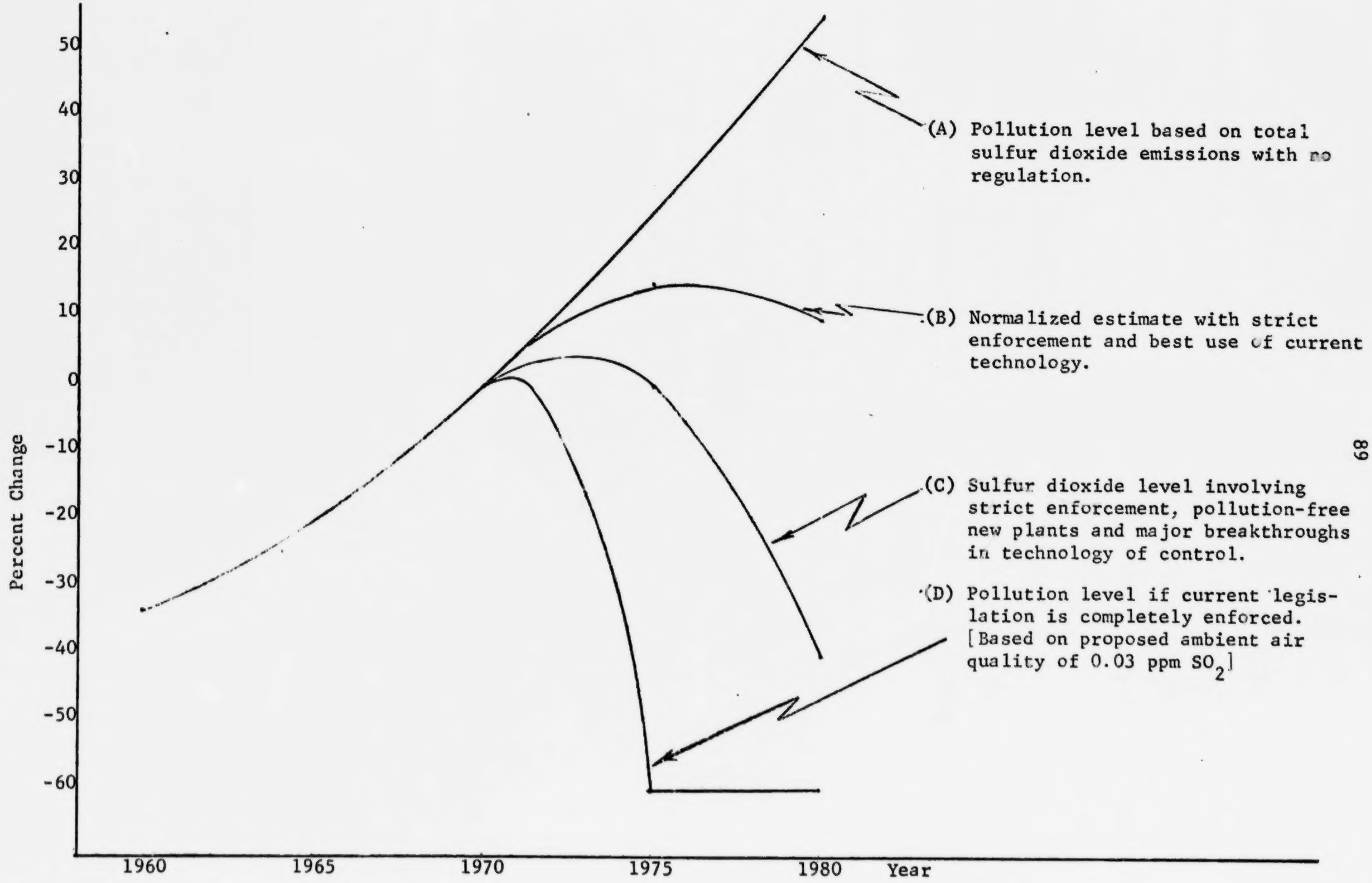
Sulfur dioxide levels in 1980 will be determined by the interaction of regulatory, economic, and technical aspects of the problem. At this time, four possibilities are seen:

Case A. If there is no regulation of pollution, the projected consumption of sulfur bearing fuels will result in an increase in the rate of sulfur oxide emissions by about 55 percent in 1980. This trend is shown by curve A of Figure 3.

Case B. This case is based essentially on today's technology and takes into consideration the availability of low sulfur fuels, the technical difficulties of enforcing pollution regulations especially with space heating and older power plants, and the general reluctance on the part of some owners to accept the higher costs involved in converting over to pollution-free methods. In this case, the normalized prediction is for an increase of 15 percent pollution in 1975, dropping to 10 percent by 1980 as is depicted by curve B in Figure 3.

Case C. This case is based on the present strong public demand for cleaner air and the efforts of federal and local authorities to respond to this pressure. It appears that research in air pollution control will be greatly expanded in the immediate future. This will increase the probability of major breakthroughs in the technology of pollution control. The results of research combined with strict enforcement will lead to a 40 percent reduction in atmospheric contamination by 1980 as shown in Curve C of Figure 3. Some slippage is allowed for in the enforcement of the new regulations for older plants where limited space and lack of finances may delay the implementation of suitable corrective measures.

Case D. If current legislation, plus that about to be enacted, is applied without exception to all users of fossil fuels, the amount of sulfur dioxide emission will be reduced 60 percent by 1975 and continue at this level beyond 1980. This result is depicted as Curve D in Figure 3.



(A) Pollution level based on total sulfur dioxide emissions with no regulation.

(B) Normalized estimate with strict enforcement and best use of current technology.

(C) Sulfur dioxide level involving strict enforcement, pollution-free new plants and major breakthroughs in technology of control.

(D) Pollution level if current legislation is completely enforced. [Based on proposed ambient air quality of 0.03 ppm SO_2]

FIGURE 3. TRENDS IN SULFUR DIOXIDE POLLUTION EXPRESSED AS PERCENT

The other factor affecting corrosivity of the atmosphere is a change in the humidity or moisture. From ASTM panel studies, and from an examination of the corrosion literature, there does not seem to be any evidence that the corrosivity of the atmosphere has been altered significantly in any recent ten-year period by changes in the availability of moisture and related meteorological factors. In fact, ten years is a rather short period in time to expect any major trend in the climate. Where the corrosion rate has changed significantly, there is almost always evidence that a change in pollution was involved. Usually there is a correlation with increased corrosion and a higher rate of consumption of sulfur-bearing fuels in the area.

Extra Annual Corrosion Damage Costs versus Pollution Levels for 1975 and 1980

The extra annual corrosion damage costs, chargeable to pollution are a function of the corrosivity of the polluted atmosphere and the total amount of susceptible external structures exposed to contaminated air. In assessing the corrosion costs for 1975 and 1980 the effect of the items listed in Table 10 on the above two factors have been taken into consideration. The changes in pollution levels for different situations were shown in Figure 3. Considerations in regard to the amount of external steelwork in 1980 also have been presented. The newly constructed steel structures in 1980 are predicted to be 30 percent of today's external inventory, of which 20 percent would be replacement of obsolete steel systems, the rest being an increase of ten percent. In addition, another 20 percent increase would be in maintenance-free materials.

TABLE 10. ECONOMIC AND POLLUTION FACTORS USED IN ASSESSING PROBABLE COST OF CORROSION DAMAGE BY AIR POLLUTION, 1970 to 1980

		Percent Change, 1970-1980
1.	**Population Increase**	
	For Nation	11.
	For metropolitan districts	12.
2.	**Energy Production**	
	Increase in power plant capacity	78.
	Space heating plant capacity	15.
3.	**Sulfur Oxide Pollution**	
	Case A. No regulation	55.
	Case B. With regulation and improved technology	<10.
	Case C. With strictly enforced regulation and major technological breakthroughs	-40.
	Case D. Complete enforcement of current legislation	-60*
4.	**External Structures**	
	Old steel structures (decrease)	-20.
	Replacement steel	20.
	New steel	10.
	New other materials	20.
	Total change	30.
	Total increase in steel	10.

*by 1975 and through 1980.

The cost of maintaining the older structure, among the 80 percent of the 1970 steel systems still in use in 1980, is likely to increase even with improved technology in corrosion control and increased use of labor saving techniques. Offsetting this will be the lower costs, in 1970 dollars, of maintaining new structure incorporating design and other features to reduce maintenance expense.

These costs are expected to balance out somewhat. Thus, allowing for some increase in both steelwork and in population, it is predicted that if there were no change in pollution, the per capita annual corrosion cost will be essentially the same in 1980 as it is today.

On this basis and taking into account the four pollution cases depicted in Figure 3, the per capita extra annual maintenance costs were established and then converted to a national basis. These results, summarized in Table 11, are discussed below:

Case A. With no regulation and a corresponding pollution increase of 55 percent by 1980, the per capita cost will increase from $7.10 to $9.22. The corresponding annual loss for the Nation will increase from $1.45 to $2.10 billion.

Case B. With regulation applied where feasible, and with full use of today's technology of control, the predicted pollution level will be 10 percent higher in 1980. This will result in a per capita increase from $7.10 to $7.63. The annual loss for the Nation will increase from 1.45 to 1.73 billion, an increase of about 0.3 billion.

TABLE 11. SUMMARY OF ESTIMATED ANNUAL AIR POLLUTION CORROSION DAMAGE TO METALS FOR 1975 and 1980.*

	Percent Change in Average Pollution	Annual Loss in Billion Dollars	Per Capita Loss in Dollars
A. No Regulation and Projected Increase in Sulfur Bearing Fuel			
1970	0	1.45	7.10
1975	25	1.78	8.26
1980	55	2.10	9.22
B. Regulation Compatible with Full Use of Current Technology			
1970	0	1.45	7.10
1975	15	1.68	7.80
1980	10	1.73	7.63
C. Strict Regulation Plus Major Breakthroughs in Control Technology			
1970	0	1.45	7.10
1975	0	1.53	7.10
1980	-40	.99	4.36
D. Complete Enforcement of Current Legislation			
1970	0	1.45	7.10
1975	-60	.47	2.20
1980	-60	.50	2.20

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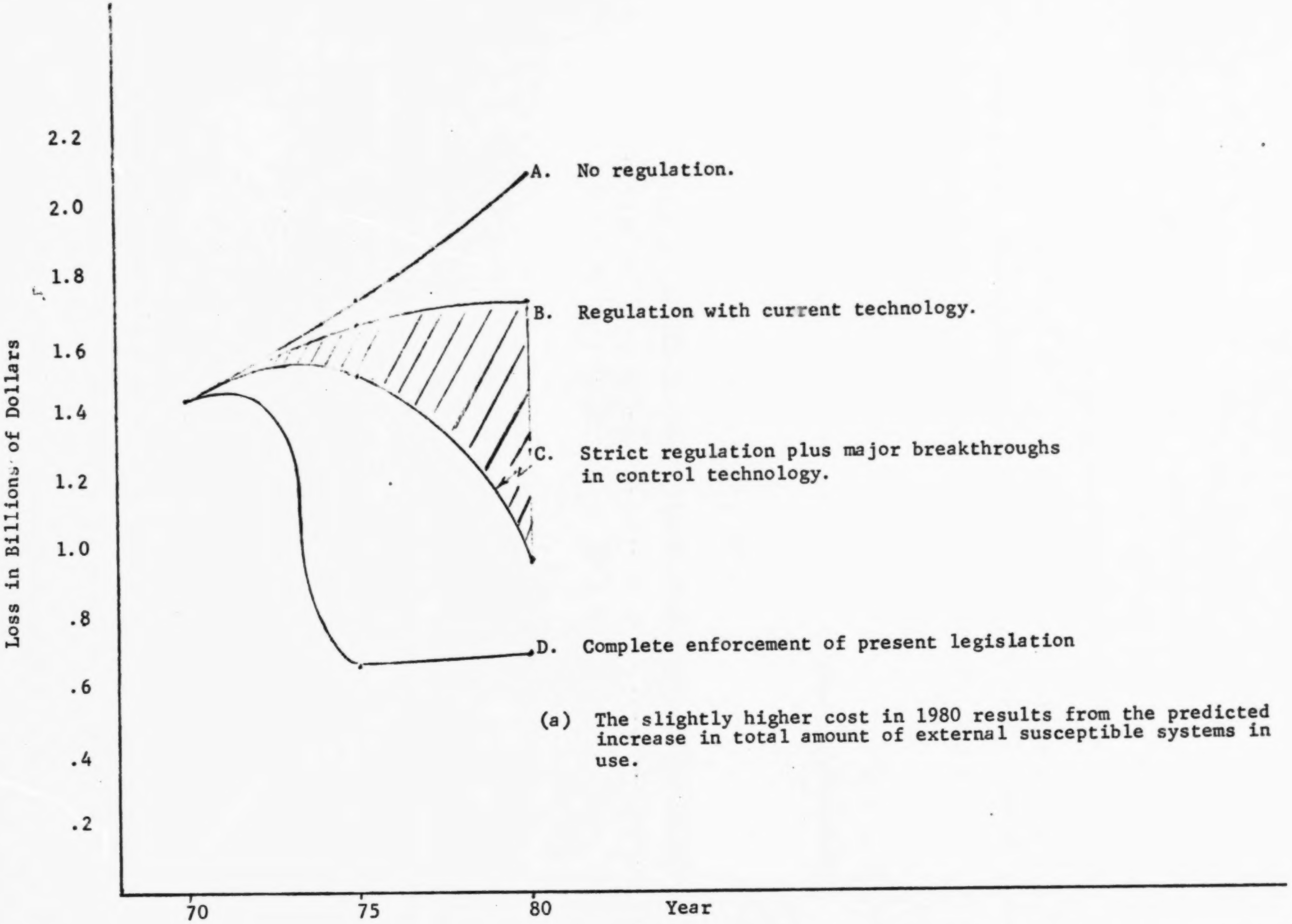
*Based on changes in pollution shown in Figure 3, changes in population shown in Figure 1 and changes in external structures shown in Figure 2.



(a) The slightly higher cost in 1980 results from the predicted increase in total amount of external susceptible systems in use.

FIGURE 4. COST OF AIR POLLUTION CORROSION DAMAGE TO METALS BASED ON CHANGES IN AIR POLLUTION SHOWN IN FIGURE 2.

Case C. With strict regulation and major breakthroughs in the technology of pollution control, the pollution is predicted to decrease 40 percent by 1980. This will lower the per capita cost from $7.10 to $4.36. The annual loss will be reduced from $1.45 to $0.99 billion, a saving of almost $0.5 billion.

Case D. With complete enforcement and a reduction of 60 percent in pollution, the per capita cost will decrease from the current $7.10 to $2.20 by 1980. The annual loss of $1.45 for 1970 will be reduced almost one billion to 0.5 billion.

The total costs to the Nation for each of the four cases as listed in Table 14 for 1970 to 1980, have been plotted in Figure 4. The cross hatched area in the figure depicts the most likely range of probability, namely from an increase of $0.3 billion to an actual saving of as much as $0.5 billion over today's cost of $1.45 billion.

RECOMMENDATIONS

Numerous engineers, supervisors, and maintenance specialists faced with the problem of keeping external steel structures and systems exposed to air pollution in good repair, were interviewed during the course of this project. In many cases, corrosion damage by air pollution is considered a normal cost of operation.

By cooperative arrangements, it is recommended that utilities, industries, and local governments be encouraged to develop cost records relating to the corrosion damage resulting from pollution. This information, once developed, could be incorporated into a state-of-art report. Sections in the report would deal with labor-saving maintenance procedures, savings resulting from the use of alternate materials, and the relative advantages of different types of corrosion control in polluted atmospheres. This report, if widely disseminated, would assist those responsible for design or for maintenance in reducing costs.

In particular there is a need for better cost records of the performance of the more popular generic paint systems in protecting steel in clean and polluted areas on actual structures and at test stations.

As a result of APCO's own research, as well as that conducted by ASTM and other agencies interested in atmospheric corrosion, the rate of attack for iron and for zinc in air of known humidity and sulfur oxide content, can be predicted with considerable accuracy. No such correlation appears to be available for the performance of steel in polluted air when protected by each of the generic paint systems now recommended for such services. It is suggested that such a program be inauguarated. One phase would consist of the evaluation of paint panels at test sites of known industrial pollution and the other would be a comparison of actual structures in industrial and in rural environments. Both performance in polluted air and cost comparisons would be developed.

Another aspect of external corrosion that was frequently mentioned in discussions with experts is the cost of damage by deicing salts. For fixed structures like guard rails, traffic signs, mail deposit boxes, metal posts, bridge decks, etc., and for mobile equipment especially automotive transport, the total cost of salt damage per year is likely to be higher than that obtained for air pollution. In view of the serious effect deicing salt has on the economy, it is recommended that an investigation be undertaken to establish the probable magnitude of these losses.

REFERENCES

1. Robbins, Robert C., "Inquiry into Economic Effects of Air Pollution on Electrical Contacts", Final Report, Contract PH-22-68-35 by Standford Research Institute, Menlo Park, California for APCO, April 1970.

2. Survey and Economic Assessment of the Effects of Air Pollution on Electrical Components, Contract CPA-70-72 by International Telephone and Telegraph Corporation, Electro Physics Laboratory Incorporated (In Progress).

3. Uhlig, H. H., "The Cost of Corrosion to the United States", Corrosion, 6, No. 1, 29-33 (Jan. '50).

4. Keynes, A., "Economic Aspects of Corrosion", Chemistry and Industry No. 14, 398-400 (April 5, 1958).

5. Harvey, C. C., "Economic Factors of Atmospheric Corrosion Protection", API Proceedings, 33, Section III (refining), 286-290 (1953).

6. Salmon, R. L., "Systems Analysis of the Effects of Air Pollution on Materials", Final Report, MRI Project No. 3323-D, January, 1970.

7. Revenue Procedure 62-21, U.S. Treasury Department, IRS Publication No. 456, August, 1964.

8. Hudson, J. C.,& Stanners,JF, "The Effect of Climate and Atmospheric Pollution on Corrosion, J. Appl. Chem., 3, p 86-96 (Feb. '53).

9. Schrier, L. L., (editor), "Atmospheric Corrosion", Vol. I, *Corrosion of Metals and Alloys*, p 2.3 to 2.12 (1963).

10. Haynie, F. H., and Upham, J. B., "Effects of Atmospheric Sulfur on the Corrosion of Zinc", Materials Protection and Performance, 9, No. 8, 35-40 (1970).

11. Ludwig, J. H., Morgan, G. B., and McMullen, T. B., "Trends in Urban Air Quality", Trans. Amer. Geophys. Union, 51, No. 5, 468-475 (May '70).

12. Stephens, E. R., "Chemistry of Atmospheric Oxidants", Jrnl. of Air Poll. Contr. Asso. 19, No. 3, 181-185 (Mar., '69).

13. Stern, A. C., "The Changing Pattern of Air Pollution in the United States", American Industrial Hygiene Association Journal, 28, No. 2, 161-5, (Mar.-Apr. '67).

14. Baulch, D. W., "Relation of Gustiness to Sulfur Dioxide Concentration", Jrnl. A. Poll. Control Assoc., 11, No. 11, 873-878 (November, 1969).

REFERENCES continued

15. Boyer, A. E., and Kaylor, F. B., "Can The Cost of SO_2 Pollution Control be Reduced?", Power, 111, 81 (April, 1969).

16. Thompson, D. H., "Atmospheric Corrosion of Copper Alloys", p. 129-140, cf. Ailor and Coburn in Bibliography.

16.5. Scholes, I. R., and Jacob, W. R., "Atmospheric Corrosion of Copper and Copper-Base Alloys during Twenty Years' Exposure in a Marine and an Industrial Environment", Jrnl. Inst. Metals, 98, 272-80, (1970).

17. Ailor, W. H., "Aluminum Corrosion at Urban and Industrial Locations", Jrnl. of the Structural Div., ASCE, 95, No. ST10, 2141-2160 [Proc. Paper 6828, October, 1969].

18. "Guide to Better Anodized Finishes", Metal Progress 93, No. 6, 60-66 (June, 1968).

18.5. McGeary, F. L., Englehart, E. T., and Ging, P. J., "Weathering of Aluminum", Presented at NE Regional NACE, Pittsburgh, Pennsylvania, October, 1965 (Alcoa Reprint).

19. Larrabee, C. P., and Ellis, O. B., "Corrosiveness of Various Test Sites as Measured by Specimens of Steel and Zinc", Proc. ASTM 59, 183-201 (1959).

20. Larrabee, C. P., "Corrosion Resistance of High Strength Low-Alloy Steels as Influenced by Composition and Environment", Corrosion, 9, No. 8, 259-271 (August, 1953).

21. Bigos, J., Good Painting Practice, Vol. 1, Steel Structures Painting Council, Pittsburgh, Pennsylvania, 1954 [Chapters 7, 9, 10, and 13].

22. Davies, C., and Hanford, N. J., "Metallic Coatings for the Protection of Metal Steel From Corrosion at Ambient Temperature", Anti-Corrosion, 17, No. 9, 17-22 (September, 1970).

23. Horvick, Ernest W., "What to Consider in Specifying Zinc Coatings, Metal Progress, 97, No. 6.

24. Porter, F. C., "The Hot Dip Galvanizing Industry", Metallurgia, 75, 241-247 (June, 1967).

25. Wachter, Aaron, "Relation of Corrosion to Business Costs", Corrosion, 10, No. 9, 273-78, September, 1954.

26. Charlton, F. R., "The Economics of Corrosion Control by Protective Coatings", Corrosion Technology 12, 11-16 (January, 1965).

27. Fancutt, F., and Hudson, J. C., Protective Painting of Structural Steel", The MacMillan Company, New York, 1957.

28. Holbrow, G. L., "Atmospheric Pollution: Its Measurement and Some Effects on Paint", Jornl. Oil Col. Chem. A., 45, 701-719 (October, 1962).

29. Keane, John D., "Protective Coatings for Highway Structural Steel", Highway Research Board, Washington, D.C., Report 74, Results of Survey (1969), Report 74A, Literature References (1012) and Abstracts (1970), Report 74B, Current Highway Practices (1970).

REFERENCES continued

29.5. Munger, C. G., "Underfilm Problems That Lead to Coating Failure", Corrosion Control Reporter (Amercoat Corp.) 8, No. 1, 2-3,7.

30. Keane, J. D., Wettach, W., and Bosch, W., "Minimum Paint Film Thickness for Economical Protection of Hot-Rolled Steel Against Corrosion", 41, No. 533, 372-82 (June, 1969).

30.5. Mills, H. E., "Costs of Process Equipment", Chemical Engineering, 71, 133-156, (March, 1964).

31. Brouillette, C. V., "Cost Comparison of Protective Coatings for Steel", NCEL Supplement, Technical Report R-501-Y-F020-03-01-001, (November, 1967). NFEC.

32. Cran, J. A., and Park, Ian M., "Bridging with Steel", Engineering Journal, 50, No. 2, 18-24 (February, 1967).

33. Radecke, F. T., "Selection of Paints and Application in Combating Atmospheric Corrosion", API Proc. 34, Sect. III, 37-49 (1956).

34. Pierce, R. R., "Key to Savings in Painting Costs", Chemical Engineering, 59, 149-53 (May, 1952).

35. Lynn, D. A.,and McMullen, T. B., "Air Pollution in Six Major U. S. Cities as Measured by the Continuous Air Monitoring System", Jrnl. A. Poll. Contr. Asso. 16, No. 4, 186-190 (April, 1966).

36. Larsen, R.I., "Relating Air Pollution Effects to Concentration and Control", Jrnl. Air Poll. Contr. Asso., 20, No. 4, 214-225 (April, 1970).

37. Thomas, M. D., "Review of Recent Studies of Sulfur Oxides as Air Pollutants", Jrnl. of the Air Poll. Control Asso., 14, No. 12, 517-520 (December, 1964).

38. Tebbens, B. D., "Gaseous Pollutants in the Air", Vol. I, Chapter 2, P. 23-46, in Air Pollution: Air Pollution and Its Effects, A. C. Stern, editor, 1968, Academic Press.

39. Blade, E., and Ferrand, E. F., "Sulfur Dioxide Pollution in New York City", Jrnl. A. Poll. Control Asso., 11, No. 11, 873-878 (November, 1969).

40. "Municipal Water Facilities--Communites of 25,000 Population and Over, United States and Possessions", A Report, U. S. Dept. of Health, Education, and Welfare, Division of Water Supply and Pollution Control, Washington, D.C. 20201, January, 1964.

41. News Release, October 13, 1970, by Department of Transportation, Federal Highway Administration, Washington, D.C. FHWA-516.

42. Private communication from Paul Mara, Aluminum Association, New York City, January, 1971.

43. Schmitt, R. J., and Mathay, W. L., "Tests Show Performance of Low Alloy Steels in Chemical Plant Environments", Material Protection, 6, No. 9, 37-41.

44. Bureau of Census, Current Population Reports, Series P-25.

45. Rohrman, F. A., Steigerwald, B. J., and Ludwig, J. H., "SO_2 Pollution: The Next 30 years", Power, 113, 82-83 (May, 1967).

REFERENCES continued

46. *Statistical Year Book of the Electric Utility Industry for 1969*, Edison Electric Institute, New York, New York, September, 1970.

47. From staff specialists in economic trends; the range predicted is 4-6 percent per year.

48. American Iron and Steel Institute, "Annual Statistical Report", (1968).

49. *Year Book of the American Bureau of Metal Statistics for the Year 1969*, (June, 1970).

50. Private discussion with H. J. Eppihimer, Porter Paint Company, Cincinnati, January, 1971.

51. *Petroleum Facts and Figures - 1967 Ed.*, American Petroleum Institute, New York, New York.

52. Erickson, E. L., and Morgan, N. W., "Painting of Highway Bridges and Structures", Chapter 10 of Reference 21, p 237.

53. "Aluminum Electrical Structures by Alcoa", Aluminum Company of America, 1961.

54. Pohlman, J. C., "What Price Maintenance Free Structures", Electrical World, 159, No. 12, 72-74 (March 25, 1963).

55. "Performance and Maintenace of Industrial Fences in Corrosive Environments", Materials Protection 4, No. 8, 8-15 (1965).

BIBLIOGRAPHY

Ailor, W. H., and Coburn, S. K., (Editors), "Metal Corrosion in the Atmosphere", ASTM STP 435, 1968 (June, 1967, meeting).

Ailor, W. H., "World-Wide Atmospheric Test Program", Corrosion Technology, 12, 12-17 (November, 1965).

Ailor, W. H., and Coburn, S. K., (Co-Chairman), Metal Corrosion in the Atmosphere, ASTM STP- 435, 1968 (Papers from 70th Annual Meeting, Amercian Society of Testing and Materials, June, 1967.

Bigos, J., Greene, H. H., and Hoover, G. R., "Five-Year Test Results: AISI Research Project on Paintability of Galvanized Steel", Jrnl. Paint Technology, 39, No. 508, 316-27 (May, 1967).

Barton, V. K., "Der Einfluss von Staub Auf Die Atmospharische Korrosion von Mettallen" (The Effects of Dust on the Atmospheric Corrosion of Metals), Werkstoff und Korrosion, 9, No. 10, 547-9, 1958.

Covy, C. J., "Effect of Atmospheric Corrosion on Maintenance and Economics of Overhead Line Hardware and Guy Strand", Corrosion, 4, No. 4, 133-140, No. 5, 207-218; No. 5, 287-303.

Coburn, S. K., "A Low-Cost Maintenance-Free Structural Steel for Highway Applications", Highway Research Record, 110 (1966), U. S. Steel Corporation, Reprint.

Christofferson, D. W., "Steel Tank Maintenance", Water and Wastes Engineering, 4, No. 3, 52-55 (March, 1967).

Downing, D. F., and Marsh, D. E., "Bridge Coating-Paint Maintenance Program Costs Over a Million Dollars Per Year--", Corrosion, 17, No. 4, 26-33 (April, 1961).

Eberhardt, T. J., "Maintenance of Galvanized Steel Towers and Substation Structures", District Conference Paper No. DP 62519, Am. Inst. of Elect. Engrs., Memphis, Tennessee (April, 1962), see also Am. Painter and Decorator, 38, No. 9, 28-30, 32 (1961).

Ewing, R. C., "Planned Maintenance Means Better Mileage From Storage Tanks", Oil and Gas Journal, 80-88 (January 23, 1967).

Faith, W. L., "Economics of Air Pollution Effects versus Cost of Control", Jrnl. of Air Poll. Assn., 13, No. 8, 363-4, August, 1963.

Frazier, J. W., "A Kansas County Replaced Old Bridges Economically", Civil Engineering-ASCE, 40, 68-70, January, 1970.

BIBLIOGRAPHY continued

Godard, H. P., et.a., The Corrosion of Light Metals, p 92-104, John Wiley & Sons, Inc., 1967.

Golden, J., and Morgan, T. R., "Sulfur Dixoide Emissions from Power Plants: Their Effect on Air Quality", Science, 171, 381-383 (January 29, 1971).

Greenblatt, J. H., and Pearlman, R., "The Influence of Atmospheric Contaminants on the Corrosion of Steel", Chem. Canad 14, 212-5, November, 1962.

Harrison, J. B., "Prediction of Perfomrance of Primers and Its Relationship to the Performance of a Full Paint System in Practice", British Corrosion Journal, 4, 58-65 (March, 1969).

Hall, J. R., "The Protection of Bridges by Galvanizing", Corrosion Prevention and Control, 17, No. 2, 12-15 (April, 1970).

Helms, F. P., "New Concepts of Zinc[paint] Coatings Reduce Maintenance Costs", Amercoat Corporation, Corrosion Control Rep., 8, No. 1, 4-6 (1958).

Kemp, W. E., "Product Fallout--A Serious Corrosion Problem", Ind. Eng. Chem., 51, 75A-76A, (July, 1959).

Long, J. B., "The Abilities of Terne Plate", Tin and Its Uses, No. 79, 5-6, (1968).

Mead, J. W., (Editor), The Encyclopedia of Chemcal Process Equipment, p. 941 (1964).

Messhem, R. B., "The Protection of Galvanized Steel", Corrosion Prevention and Control, 16, No. 3, 22.

Melvin, J. S., "Evaluation of Some Materials and Coatings for Utility Pole-Line Hardware", Corrosion, 17, No. 4., 14-15, 18-19, (April, 1961).

Morgan, N. W., "Corrosion Problems in Highway Maintenance", see extract in Corrosion, 17, No. 4, pp 22-23 (April, 1961).

Maurin, P. G., and Jonakin, J., "Removing Sulfur Oxides From Stacks", Chemical Engineering 77, No. 9, 173-180 (April 27, 1970).

Nylen, P., and Tragardh, K. F., "Exposure Tests of Paints in Sweden", Corrosion Technology 2, 182-85 (June, 1955).

Oliver, James, "Developments in Pretreatment and Finishing of Zinc-Coated Products", 31, No. 8, 48-53, (May, 1967).

Porter, T. C., "Painting of Zinc Surfaces", Br. Corr. Jrnl., 4, 179-186 (July 1969).

Popper, H., Modern Cost Engineering Techniques, McGraw Hill Book Company, (1970).

BIBLIOGRAPHY continued

Reid, W.T., "What About Air Pollution by Power Plants?", Battelle Research Outlook, 2, No. 3, 21-23 (1970).

Rohrman, F. A., Steigerwald, B. J., and Ludwig, J. H., "SO_2 Pollution: The Next 30 Years", Power, 113, 82-83 (May, 1967).

Rugger, George R., "Weathering Resistance of Plastics", Materials in Design Engineering, 59, 69-84 (January, 1964).

Robinson, E., and Robbins, R. C., "Gaseous Sulfur Pollutants from Urban and Natural Sources", Jrnl. A. Poll. Control, Asso. 20, No. 4, 233-235 (April, 1970). See also American Petroleum Institute Report "Sources, Abundance, and Fate of Gaseous Atmospheric Pollutants", February, 1968, by same authors (SRI PR-6755).

Shepard, D. S., "A Load Shifting Model for Air Pollution Control in the Electric Power Industry", Jrnl. APCA, 20, No. 11 p 756-761.

Sareda, R. J., "Atmospheric Corrosion of Steel", Ind. Eng. Chem., 51, No. 9, pt. 1, 79A-80A (September, 1959), and "Atmospheric Factors Affecting the Corrosion of Steel", Ind. Eng. Chem 52, No. 2, 157-160 (February, 1960).

Still, J. M., Jr., :Wheels are Turning for Terne Products", Iron Age, 94, 28, (October 15, 1964).

Stanners, J. F., "Use of Environmental Data in Atmospheric Corrosion Studies", British Corrosion Journal, 5, 118-121 (May 1970).

Smith, D. W., and Day, K. J., "Protection of Steel Bridges from Corrosion", British Corrosion Journal, 5, 151-158 (July, 1970).

Squires, A. M., "Keeping Sulfur Out of the Stack", Chemical Engineering, 77, No. 9, 181-89 (April 27, 1970).

Spirtos, R., and Levin, H. J., "Characteristics of Particulate Patterns," 1957-1966, AP-61, HEW.

Tice, E. A., "Effects of Air Pollution on the Atmospheric Corrosion Behavior of Some Metals and Alloys", Jrnl of The Air Pollution Control Association, 12, No. 12, 553-559 (December, 1962).

Tropp, F. E., "Evaluation of Zinc Surfaces for Coating Industrial Production Line Products", 39, No. 507, 225-254.

Urone, Paul and Schroeder, W. H., "SO_2 in the Atmosphere--" Environmental Science and Technology, 3, No. 5, 436.

BIBLIOGRAPHY continued

Yocom, J. E., and McCaldin, R. O., "Effect of Air Pollution on Materials and the Economy", Vol. I, Chapter 15, 617-651, Air Pollution: Air Pollution and Its Effects, AC Stern, editor, 1968, Academic Press.

"Alcan Handbook", Aluminum Company of Canda, 1970.

"Atmospheric Effects Can Be Correlated", Canadian Chemical Processing, 51, No. 8, 40-43 (August, 1967).

Aluminum Statistical Review, The Aluminum Association of New York, (1969).

"Air Pollution versus Materials Costs", Materials Protection, 6, 47-54, May, 1967.

"Long Terne Sheets Long on Processability", Metal Progress, 97, No. 6, 7-8, (June, 1970).

Steel Products Manual "Carbon Sheet Steel, Coils, and Cut Lengths", American Iron and Steel Institute, May, 1970.

Metal Statistics, 1969, The American Metal Market Company (Also daily issues of The American Metal Market).

Bureau of Census-Pocket Data Book, USA-1969.

Statistical Abstract of the United States-1970.

APPENDIX A

COMPUTATION OF UNITS AND/OR WEIGHT OF SYSTEMS IN USE AT CURRENT TIME

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APPENDIX A

COMPUTATION OF UNITS AND/OR WEIGHT OF SYSTEMS IN USE AT CURRENT TIME

Air pollution corrosion costs are found in this study to be equal to the cost of maintaining components over the lifetime of the system in which they appear. Specifically, lifetime maintenance cost is the total number of paintings, n, time the cost of one paint job, p, over the useful and depreciable lifetime of the system, according to equation 7, page 17.

Beginning with a number for the lifetime of any given system, the number of paintings, n, is the lifetime of the system divided by the lifetime of a single paint job. While the numerator is constant, the denominator decreases with increased air pollution and n increases with increased air pollution.

The cost of a paint job is the cost of paint and application per unit area, times the total area of the component. Therefore total area of all certain components in certain systems in use at the moment needs to be determined. That total area of all certain components is the weight of such components in use divided by the area per average sized component; or it is the number of such components in use times the area per average sized component.

The purpose of Appendix A is to describe the procedure used to determine the weight of specific systems in useful service as of 1970.

Consonant with real-value theory each specifically defined system has an acceptable useful and depreciable lifetime, given in years. Many tanks, for example, are in use long after their depreciable lifetime of 50 years is exhausted, while others are torn down earlier.

The useful and depreciable lifetime of systems are defined roughly at the 4-digit level of the Standard Industrial Code, and have been statistically established by the U.S. Department of Internal Revenue, and published in "Depreciation Guidlines and Rules", Revenue Procedure 62-21. For example, it sets the statistical useful lifetime of 13 various buildings, such as apartments at 40 years, dwellings at 50 years, warehouses at 60 years, etc. Also, it sets agricultural machinery and equipment at 10 years, recreation and amusement systems at 10, logging equipment at 6 years, and fences, bridges, shop machinery, etc., at 30 years, and many others. These lifetimes are accepted as tax write-off guidelines, and are used as starting points for calculating assessed values of individual properties or systems by assessors. They are used here for what they are; the statistically average useful lifetime of all systems so designated by 4-digit terminology.

System lifetimes are used in this report to compute the number, or weight of specific systems in useful service by integrating shipment data from 1970 back over its lifetime of useful and presently depreciable years as depicted in Figure A-1. Data from the Census of Manufactures normally provides points for the years shown, 1967, 1963, 1958, 1954, and 1947. For some systems still earlier figures are available. For more recent years, annual statistics may for some systems fill in points between 1967 and 1963. Where in-between data points are missing, interpolated points are computed on a straight line. Points between 1967 and 1970 are extrapolated either on a line representing average industrial growth for the system in question, or on a slope which by inspection appears to be reasonable.

The integrated total, if in units, is converted to total weight on the basis of average size and weight of this average unit as indicated in manufacturers design literature. From data in these same sources, the tonnage can be converted to air-exposed area equivalents.

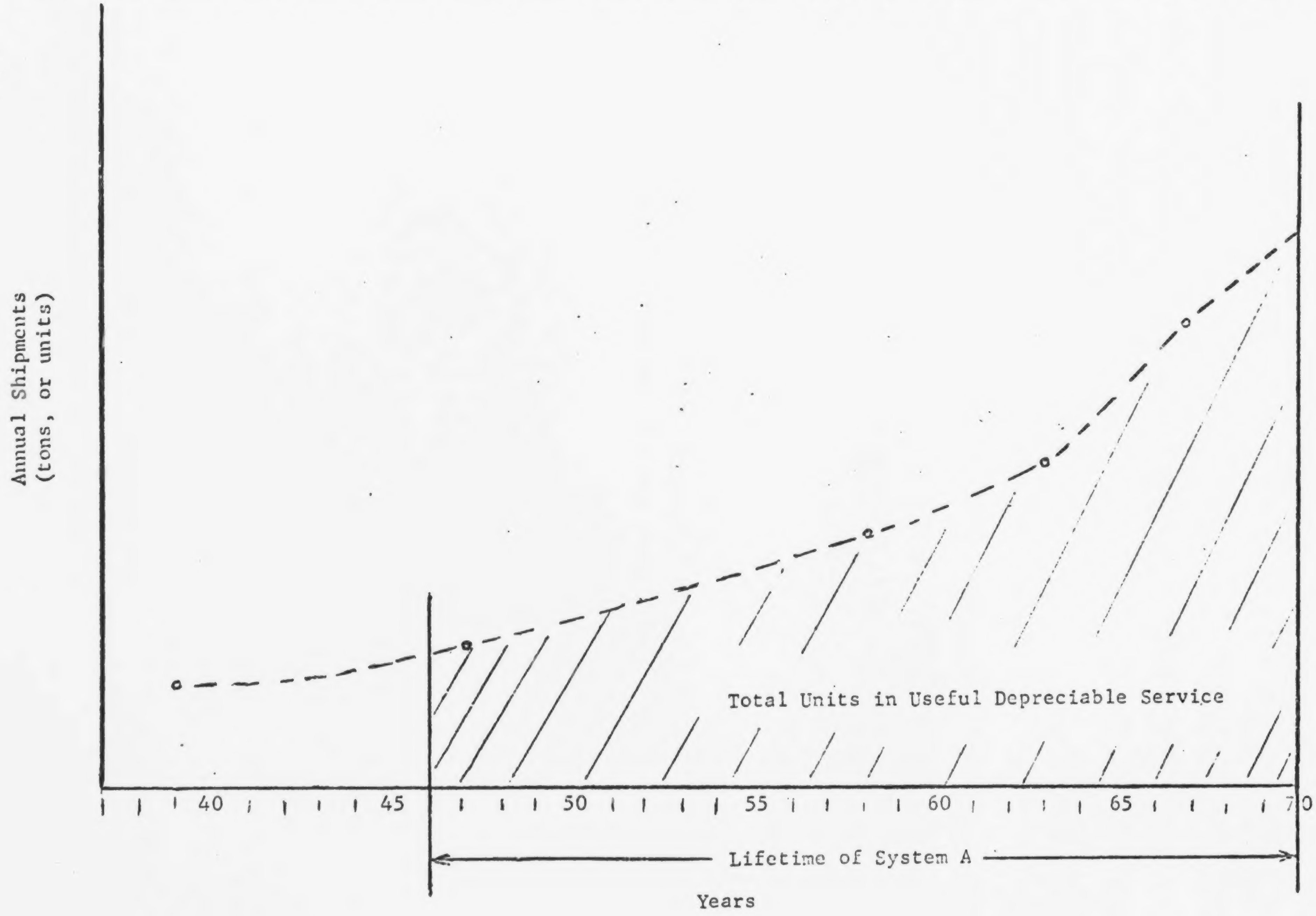

FIGURE A-1. ANNUAL SHIPMENTS OF SYSTEM A

An example is given in Tables A-1 and A-2 for 36122-power distribution transformers. In Table A-1, two years are shown with the product mix breakdown for 1963 and 1958. Wherever such breakdowns were given, the year totals were built on the indicated product mix. Only data on latter years provided such refinement, however.

In Table A-2 the underlined years are data points, and the others are interpolations or extrapolations.

TABLE A-1. 36122 - POWER DISTRIBUTION TRANSFORMERS

3612 - Pwr.,Distr., & Spec'ty Txfmrs	1963				1958			
	#Units	Total KVA 10^3	$\$10^3$	Surf. Ar. sq. ft.	#Units	Tot KVA 10^3	$\$10^3$	Surf. Ar. sq. ft.
36 12 2 - Pwr.Distr.Txfmrs.								
06- <15 KVa < 15,000 V (Pole type,11.2 ft^2/unit)	419,400	4,889	80,155	4,697,280	314,394	3,552	76,093	3,521,213
08- 16-50 KVA, < 15,000 V (Pole type,21.1 ft^2/unit)	320,135	9,894	91,967	6,754,638	137,844	7,188	87,315	2,908,508
12- 51-167 KVA, < 15,000 V (Pole type,A = 30 ft^2/unit)	74,282	7,864	60,748	2,228,460	33,337	3,781	30,481	1,000,110
14- 168-500 KVA, < 15,000 V 500 KVA>15,000 V (Station type,=138 ft^2/unit)	11,435	3,992	24,041	1,577,616	7,281	2,338	23,580	1,004,778
16- 501-5000 KVA, all E (Station Type,A=175 ft^2/unit)	8,705	12,196	60,128	1,523,375	5,319	7,771	66,417	1,359,925
17- 5001-10,000 KVA, all E (Station type,A=175 ft^2/unit)	697	5,240	18,795	121,975	661	5,172	23,491	115,675
21 23 Over 10,000 KVA, all E (Primary sub sta, A = 208 ft^2/unit)	860	59,858	97,501	178,880	677	34,210	108,279	140,816
00- Pwr, distr txfmrs, n.s.k. (208 ft^2/unit)	2,231	277	1,159	464,058	2,060	255	1,070	428,480
TOTAL UNITS,$\$10^3$VALUE	837,745	104,206	434,494	17,546,272	501,573	64,267	421,726	10,479,505
(FT^2) TOTAL	17,546,272							
(YRS) LIFETIME	30							
(FT^2) LIFETIME INVESTMENT AREA	556,630,000							

TABLE A-2. INTEGRATIONS OF POWER DISTRIBUTION TRNASFORMERS IN VARIOUS UNITS

(Average lifetime = 30 years)

Year	Number of Units	Total KVA x 10^3	Total Area Ft^2	Total Value $\$10^3$
1970	1,600		33,440	830
9	1,542		32,228	800
8	1,494		31,225	775
1967	1,443,947	180,017	30,242,884	748,900
6	1,272		26,585	660
65	1,157		24,181	600
4	964		20,147	500
1963	837,745	104,206	17,546,272	434,494
2	769		16,072	432
1	700		14,630	429
60	634		13,251	427
9	566		11,829	424
1958	501,573	64,267	10,479,505	421,726
7	531		11,098	427
6	560		11,704	431
55	591		12,352	436
1954	623,565	78,947	13,026,273	441,089
3	773		16,156	407
2	894		18,685	374
1	979		20,461	340
50	1,032		21,569	307
9	1,051		21,966	273
8	1,042		21,778	240
1947	994,386	125,895	20,072,924	205,943
6	903		18,873	187
45	807		16,866	167
4	715		14,944	148
3	618		12,916	128
2	526		10,993	109
1	435		9,092	90
40	338		7,064	70
1939	246,275	32,231	5,157,000	51,005
TOTALS			566,630,000	12,316,000

APPENDIX B

SCREENING PROCEDURE FOR DEFINING SYSTEMS AND COMPONENTS

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APPENDIX B

SCREENING PROCEDURE FOR DEFINING SYSTEMS AND COMPONENTS

If the cost of air pollution corrosion is to be limited to real costs, or losses in the value of systems, then a determination of the most vulnerable, valuable, and expensive component systems is the first order of business. This determination began with component/system definition, with the aid of the SIC array, and continued through a series of qualitative screenings, evaluations, and simplifications.

The first step was to identify the two broadest categories, Construction, Division C, and Manufacturing, Division D, as the SIC groupings in which all the component systems would appear. Other divisions represent services and/or utilizers of the component/systems contained in Divisions C and D.

Construction contains the largest exposure of metal components. Manufactured products also contain a great deal of metal, but mostly serving either in a protected environment, or in a hostile environment made malignant by excessive heat, stress, corrosion and other conditions that really mask the less aggressive air pollution sector of the out-of-doors environment. These generalizations were less clear at the outset of the study. To realize these observations, however, makes it easier to follow the extensive, complicated screening process pursued by this study.

In the first stages of the project, however, this was not realized. What the team saw were two large bodies of SIC statistics on systems of construction and systems of manufacturing. That some manufactured products went into construction was clear enough, but their preponderant importance was obscure, and perhaps not even credible at that moment. In addition, the philosophical starting point was at the surface vulnerable to air pollution corrosion, while value data was far down the line at the component and systems levels. Somehow the two extremes would have to be linked in a practical, meaningful way.

Since it is clearly impractical to tabulate every surface in every component in every subsystem in every system in existence, the study pursued a course of discrimination to eliminate low-value surfaces, surfaces in protected systems, and otherwise ones insensitive to the marginal deterioration of air pollution. Accordingly the study developed a system of screens for sorting out only corrosion sensitive component-systems of value. The screens were used to sort out and winnow down the systems and components originating in Division D--Manufacturing, a group of some 20 manufacturing industries. First the industries that manufacture metal containing systems were sorted out of these 21 Standard Industrial Classification, 2-digit categories, as follows:

25 - Furniture and Fixtures
33 - Primary Metal Industries
34 - Fabricated Metal Products
35 - Machinery, Ex.Electrical
36 - Electrical Machinery
37 - Transportation Equipment
38 - Professional, Scientific, etc.
39 - Miscellaneous Manufacturing

All others were ignored, as not generating metal containing components and systems. An exception to this is 19 - Ordnance, which does produce metal containing components and systems. That industry was eliminated early because of the general expendability of its products, the excessive aggressiveness of the service environment encountered by ordnance systems, and the fatuous protection of the storage environment encountered off duty.

Procedural Summary

The screening, winnowing and combining procedure applied to Division D--Manufacturing statistics involved five steps, as summarized in Table B-1. This procedure accomplished two things. It first showed that exposed metal components of any importance either resided on or comprised structural systems. All others were at least an order of magnitude less important according to in-situ value and tonnage. The scope of this report does not allow for elaborations on this point, interesting as it may be. The other thing the screening accomplished was to cut through an almost infinite environment of statistics and pull out the important salient portion. Fortunately, it reduced the number to a quantity that could be meaningfully handled, but barely within the resources of the project, as summarized in Table B-1.

Qualitative Screens

All the components in outdoor systems used by society suffer some deterioration from pollution. But more deterioration may occur from other extraneous service conditions, such as erosion, deicing salt, deformation, oxidation, and possibly other effects. Often these other service conditions are considerably more severe than air-pollution deterioration, and effectively mask it. Thus of prime concern is to choose from the many in existence those components and systems that are solely or mainly affected by air pollution at a cost to society. Also of prime concern is to choose those components and systems that fit value sensitive criteria, i.e., those that at once require a large amount of pollution-sensitive metal in their manufacture, are associated with systems of higher shipped value, and involve large metal requirements and/or large total surface areas.

TABLE B-1. STATISTICS OF SCREENING, WINNOWING, AND COMBINING

Screen Description	Input	Survivals	Rejects
First: qualitative	200-4-digit	60	140-4-digit
	← expansion →		
Second: qualitative	244-5-digit	51	193-5-digit
	← expansion →		
Third: eliminate Cu and Al components	101-6/7-digit	43	58-6/7-digit
Fourth: high profile items	43-6/7-digit	19	24-6/7-digit
Fifth: combine	19-6/7-digit	12 combinations	

The first qualitative screen dealt in four-digit SIC categories of metal containing components that have metal exposed to the service environments. There were 200 such categories entered into the first screen,

Within these categories reside about 1600 specific components, which when thought of in terms of alternate metals of construction multiply by that number into 4800 separate considerations. The first screen separated out for rejection those categories that appeared (a) to be insensitive to pollution, (b) to perform its function in a protected inside environment, and (c) to be subject to other more damaging service conditions (erosion, deformation, scoring, etc.) than could be occasioned by pollution corrosion. Judgments were actually exercised by a screening task force membered by corrosion engineers and by design specialists in the manufacturing industries and by materials consultants. Of the 200 categories (4-digit) which entered the first screen; 140 were rejected by task-force judgment.

A typical working format is reproduced in Table B-2. The Committee took each 4-digit category, and exercised judgment about the probable functional sensitivity of contained systems and components to atmospheric corrosion; notated their probable service sites as protected or unprotected; contemplated likely masking effects in the service environment; and finally disposed of it as an "overriding keep" for subsequent screening, "provisional keep", or "reject". If a category had even one item in it that represented a questionable reject, it was kept provisionally; or one that might contain an exceptional situation, it was overridingly kept in.

The second screen was again qualitative. First, the 60 four-digit-category survivors were expanded into 244, five-digit-category items, which were then entered into the second screening assessment. Here again, the same qualitative criteria as in the first screen were applied. One hundred nine (109) ~~items~~ 5-digit items survived the second screen and 193 were rejected.

TABLE B-2. SURVIVAL COMPONENTS FROM THE QUALITATIVE SCREENS

Sic Code	System Description	Metal Employed	Metal Rank	System Destination						
				A Indust. Non-Build. Constr.	A Resid. Home Build. Constr.	A Indust., Commer., Institutional Build. Constr.	B Gen. Constr. (Infrastructure)	CD Capital Equip.	CD Domestic Equip.	- Intransit
25	**Furniture**									
143	Metal, Porch, Lawn Outdoor	Steel	41						X	
		Aluminum	19						X	
33	**Primary Metals Industry**									
* 151	Noninsulated Wire Rope	Steel (G)	30	X			X			
* 6	Fencing & Fence Gates	Steel (G)	33	X	X	X	X			
7	Ferrous Wire Cloth & Other Woven	Steel	45		X	X				
51	Barbed & Twisted Wire	Steel (G)	39	X		X	X			
16701	C.R. Sheet & Strip	Steel	2							X
801	C.F. Bars & Shapes	Steel	8							X
000	C.R. Sheet & Strip, NSK	Steel	1							X
17601	Steel Pipe & Tube	Steel	4							X
34	**Fabricated Metal Products**									
* 411	Fabricated Structural Iron Steel for Buildings and Around Buildings	Steel	5	X		X	X			
		Aluminum	9	X		X	X			
* 2	Fabricated Structural Iron Steel for Bridges	Steel	15				X			
		Aluminum	15				X			
* 3	Other Fabricated Structural Iron Steel (Transmission Towers, Substations, Radio Antennae Towers, Aluminum for Ships, Boats, Barges)	Steel	9	X		X	X			
		Copper	12	X		X	X			
		Aluminum	18	X		X	X			

TABLE B-2. (Continued)

				System Destination						
Sic Code	System Description	Metal Employed	Metal Rank	A Indust. Non-Build. Constr.	A Resid. Home Build. Constr.	A Indust., Commer., Institutional Build. Constr.	B Gen. Constr. (Infrastructure)	CD Capital Equip.	CD Domestic Equip.	• Intransit
0	NSK	Steel	25	X	X	X	X			
* 421	Metal Doors & Frames, Exterior Storm	Steel	23		X	X				
		Copper	22		X	X				
		Aluminum	3		X	X				
* 422	Metal Window Sash, Frames, Exterior Storm	Steel	28		X	X				
		Copper	25		X	X				
		Aluminum	4		X	X				
* 423	Metal Molding, Trim, Store Fronts	Steel	22		X	X				
		Aluminum	6		X	X				
424	Metal Combination Screen & Storm Sash and Doors	Steel	42		X	X				
		Aluminum	8		X	X				
425	Metal Window and Door Screens	Steel	44		X	X				
		Copper	21		X	X				
		Aluminum	22		X	X				
420	Ditto, NSK	Steel	36		X	X				
432	Fabricated Steel Plate, Including Stacks, Weldments	Steel	12	X		X	X			

TABLE B-2. (Continued)

Sic Code	System Description	Metal Employed	Metal Rank	System Destination Indust. Non-Build. Constr. A	Resid. Home Build. Constr. A	Indust., Commer., Institutional Build. Constr. A	Gen. Constr. (Infrastructure) B	Capital Equip. CD	Domestic Equip. CD	Intransit -
* 435-9	Metal Tanks	Steel	7	X	X	X	X			
* 441-0	Sheet Metal Work (Roofing, Siding, Draining)	Steel (G)	6		X	X				
		Copper	3		X	X				
		Aluminum	1		X	X				
460	Architectural, Ornamental Metal Work (Fences, Gates, Stairs, Fire Escapes, Railings, Open Flooring Grates, Grills)	Steel (G)	19	X	X	X	X			
		Copper	15	X	X	X	X			
		Aluminum	8	X	X	X	X			
* 492	Prefabricated & Portable Metal Buildings	Steel	7	X	X	X				
		Copper	13	X	X	X				
		Aluminum	12	X	X	X				
493	Miscellaneous Metal Building Material (Curtain Walls)	Copper	18			X				
		Aluminum	5			X				
814-5	Wire Cloth, Ferrous, Nonferrous	Steel	26		X	X				
		Copper	17		X	X				
		Aluminum	25		X	X				
* 816	Fencing, Fence Gates, Exterior that made in 3315	Steel	33	X	X	X	X			
		Aluminum	15	X	X	X	X			
819	Other Fabricated Wire Products (Wire Chain, Barbed & Twisted Wire not made in 33159, Wire Baling	Steel (G)	10	X						
		Copper	9	X						
		Aluminum	28	X						

TABLE B-2. (Continued)

				System Destination						
Sic Code	System Description	Metal Employed	Metal Rank	Indust. Non-Build. Constr.	Resid. Home Build. Constr.	Indust., Commer., Institutional Build. Constr.	Gen. Constr. (Infrastructure)	Capital Equip.	Domestic Equip.	Intransit
				A	A	A	B	CD	CD	-
35	Machinery, Exterior Electrical									
351	Conveyors for Conveying Equipment	Steel	26					X		
		Copper	11					X		
		Aluminum	23					X		
2	Conveying Parts & Attachments	Steel	37					X		
		Copper	26					X		
		Aluminum	30					X		
36	Electrical Machinery									
* 122	Power & Distributor Transformers	Steel	38			X	X	X		
		Copper	10			X	X	X		
		Aluminum	31			X	X			
3	Power Regulators, Boosters, Reactors	Steel	18					X		
		Copper	1					X		
		Aluminum	21					X		
131	Switchgear, Including Power Saw, Gear Assembly	Steel	21			X		X		
		Copper	4			X		X		
		Aluminum	17			X		X		
2	Circuit Breakers	Steel	32			X		X		
		Copper	8			X		X		
		Aluminum	26			X		X		

TABLE B-2. (Continued)

				System Destination						
Sic Code	System Description	Metal Employed	Metal Rank	Indust. Non-Build. Constr.	Resid. Home Build. Constr.	Indust., Commer., Institutional Build. Constr.	Gen. Constr. (Infrastructure)	Capital Equip.	Domestic Equip.	Intransit
				A	A	A	B	CD	CD	·
220	General Industry Power Circuit Devices and Controls	Steel	24					X		
		Copper	6					X		
		Aluminum	16					X		
* 425	Outdoor Lighting Equipment	Steel	35	X	X	X				
		Copper	14	X	X	X				
		Aluminum	20	X	X	X				
6	Other Electric and Nonelectric Lighting Equipment	Steel	40	X	X	X				
		Copper	19	X	X	X				
		Aluminum	27	X	X	X				
430	Current Carrying Devices, Including Lightning Rods	Steel	31	X	X	X				
		Copper	2	X	X	X				
		Aluminum	13	X	X	X				
* 441	Pole Line & Transmission Line Hardware	Steel	28				X			
		Copper	10				X			
		Aluminum	24				X			
2	Electric Conduit & Fittings	Steel	27	X	X	X	X			
		Copper	23	X	X	X	X			
		Aluminum	10	X	X	X	X			

TABLE B-2. (Continued)

				System Destination						
Sic Code	System Description	Metal Employed	Metal Rank	Indust. Non-Build. Constr. A	Resid. Home Build. Constr. A	Indust., Commer., Institutional Build. Constr. A	Gen. Constr. (Infrastructure) B	Capital Equip. CD	Domestic Equip. CD	Intransit -
37	Transportation									
121	Auto Passenger Cars Assembled & Knocked Down	Steel	3							X
		Copper	-							
		Aluminum	-							
910	Trailer Coaches, Housing Types	Steel	17					X		
		Copper	7					X		
		Aluminum	2					X		
39	Miscellaneous Manufacture									
931	Luminous Tube & Bulb Signs	Steel	43					X		
		Copper	24					X		
		Aluminum	29					X		
2	Nonelectric Signs and Advertising Display	Steel	34					X		
		Copper	20					X		
		Aluminum	14					X		
				34	45	62	28	29	2	5

The third screen was semiquantitative, in which components were screened in terms of availability vs metal construction. First, the 51 5-digit-item survivors were expanded into 101, 6 and 7-digit component considerations, as each component was recognized as a steel item separate from copper, and aluminum, and from galvanized and vice versa. Specifically, these components included such things as aluminum storm doors, curtain wall, etc.; also copper downspouts, flashing, etc.; and galvanized wire fencing, downspouts, and flashings, etc.

Aluminum and copper components appeared not to require painting, except for cosmetic appeal, nor did they appear to have shortened service life under the influence of purely air pollution. They were, therefore, eliminated from further consideration as metals having higher costs in polluted air than in clean air. Some items were retained, however, to study the extra expense involved if aluminum or copper were substituted for high-maintenance steel systems. This elimination left 43 vulnerable steel components.

At this point, it was observed that the surviving specific components, Table B-2, are primarily found in systems of construction, i.e., buildings of all kinds, utilities installations, and infrastructure, embodying such components as bridges, towers, tanks, fencing, etc. Other systems comprising a region were eliminated as being masked by other effects. For example, mobile transportation equipment, and roadside fixtures were eliminated because they are more attacked by de-icing salts, impact of small stones, and other destructive forces than by air pollutants. All that is left is that tonnage of 19 component categories associated with construction systems. Later, the structure of the data sources made it convenient to group these together into 14 component categories distributed among, and part of outdoor-construction systems.

There are some 41 categories of outdoor-construction systems in which components appear which on a 41 by 14 matrix turns up 574 component-system cells. Some of these systems operate in rural atmospheres, however, such as social and recreational complexes and structures, while some are relatively small users of components, such as hospital and church buildings. Eliminating these narrows the number 41 down to 21, which about halves the number of cells. Then, by grouping similar items again, the number 21 reduces to nine. Thus, with 14 categories of components operating in these nine systems, there turns up statistically 126 cells, or unique component-system pairs to examine.

Among these cells are many absurdities, such as structural steel in bridges opposite electrical machinery systems and some relatively trivial, such as steel storage tanks across from residential buildings. Other pairs were reasonable, but small enough to be grouped with other similar pairs, such as steel transmission towers across from a grouping of utilities, including electric power, telephone and telegraph, airports and military construction. Happily this last grouping was essentially done for us by the manner in which statistics on components are published.

Finally, we ended up with 23 pairs of component-system and component-system groupings. Data on those pairs were developed around nine major components, and are found as breakdown headings and subheadings thereunder.

APPENDIX C

CALCULATION OF CORROSION COSTS FOR STEEL STRUCTURES AND SYSTEMS IN POLLUTED ATMOSPHERES

APPENDIX C

CALCULATION OF CORROSION COSTS FOR STEEL STRUCTURES AND SYSTEMS IN POLLUTED ATMOSPHERES

C-1 Calculation of Corrosion Maintenance for Water Storage Tanks, Petroleum Tanks, and Chemical and Industrial Tanks

C-2 Calculation of the Extra Maintenance Painting Expense, Chargeable to Pollution, for Structural Steel Bridges

C-3 Calculation of Air Pollution Corrosion Costs for Externally Mounted Power Transformers

C-4 Calculation of Losses, Based on Extra Maintenance Costs in Polluted Atmospheres for Outdoor Lighting Fixtures

C-5 Calculation of the Annual Pollution Costs Involved in Painted Outdoor Steel (Metal Work) and Galvanized Steel

C-6 Calculation of Air Pollution Costs for Galvanized Pole-Line Hardware

C-7 Calculation for Galvanized Chain-Link Fence

C-8 Calculation of Air Pollution Corrosion Costs for Galvanized Wire Rope

C-9 Calculation of the Extra Maintenance Expense for Power Line Transmission Towers Exposed to Air Pollution

C-10 Summary of Principal Data Used in Tables C-1 to C-9

C-11 Comparison of Metal Roofing for Service in a Highly Polluted Atmosphere. Annual Costs are Based on Installation Expense With No Added Maintenance

C-12 Pollution Costs of Aluminum Roofing and Siding, 1969 Statistic

C-13 Pollution Costs for Substituting Self Weathering Steel for Carbon Steel in Bridges

TABLE C-1. CALCULATION OF CORROSION MAINTENANCE FOR WATER STORAGE TANKS, PETROLEUM TANKS, AND CHEMICAL AND INDUSTRIAL TANKS

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1. Elevated Water Storage Tanks

First Estimate of Tankage Based on Volume Data

1. Total estimated storage in elevated steel tanks is 11,000 x 10^6 gallons.
2. Typically elevated storage tank = 1 x 10^6 gallons (1 MG).
3. Equivalent No. of 1 MG Tanks = 11,000.

Second Estimate Based on Steel Plate Tonnage

4. Total tonnage of steel plate in all municipal water systems is 7,100,000. Of this, some 70 percent is estimated to be in elevated storage tanks.
5. A 1 MG tank is about 350 tons.
6. Number of 1 MG tanks in service is .70 x 7,000,000 ÷ 350 = 14,300
7. Average of Item No. 3 and No. 6 = 12,700

Calculation of Pollution Cost

8. Area of hemisphere + roof = 10,050 + 5,020 = 15,070 sq.ft. Other designs range from 12,000 to 30,000 sq.ft. Use 20,000 sq.ft. for calculation.

   Annual extra maintenance cost = 0.0167 (see Table 4).

   20,000 x 0.0167 = $334/yr for 1 MG tank.

9. Based on observation, about 80 percent of the elevated tanks are exposed to contaminated atmospheres.

   Total annual extra cost caused by pollution is
   .80 x 12,700 x 334 = $3,400,000.

2. Petroleum Product Storage Tanks

First Estimate Based on Capacity

1. Bulk storage capacity (API Data) in 1962 - 17,981,306,000 gallons. Projected to 1970, using growth in petroleum production to gage capacity increase. 20,000,000,000 gallons.
2. Barrels capacity (42 gallon/barrel) = 477,000,000.

TABLE C-1 (continued)

---

2. Petroleum Product Storage Tanks

First Estimate Based on Capacity

3. A. Estimate 2/3 of refinery size, 100,000 barrels.
   B. Estimate 1/3 of distribution size, 10,000 barrels.

   A. $\frac{0.66 \times 20 \times 10^9}{4.2 \times 10^6}$ = 3,150 tanks, 100,000 barrel size. Add 10% to allow for ullage.

   B. $\frac{0.33 \times 20 \times 10^9}{4.2 \times 10^5}$ = 15,750 tanks, 10,000 barrel size. Add 10% to allow for ullage.

4. Area of tanks $C = \frac{D^2 \times H}{7.15307}$ C = capacity in barrels

   A. For 100 foot diameter, height becomes 75 feet.
   Area of cylinder plus roof $A = H\pi D$ and $\frac{\pi D^2}{4}$ = 31,450 sq.ft.

   B. For 55 foot diameter, height becomes 24 feet.
   Area of cylinder plus roof is equal to 6,530 sq.ft.

5. Annual extra maintenance cost per tank (see Table 4).

   A. 31,450 x 0.0473 =\$1,490
   B. 6,530 x 0.0473 =\$ 309

6. Total annual maintenance.

   A. 3,464 x 1,490 = \$ 5,160,000
   B. 17,325 x 309 = \$ 5,360,000
   Total \$10,520,000

Second Estimate Based on Tonnage

7. Total tons in use 1,950,000. Area Factor (one side) for Heavy Tanks is 120 sq.ft./ton

8. Loss = 1,950,000 x 120 x 0.0473 = 11,100,000
   Summary for petroleum storage, annual loss per year:
   First method 10,520,000
   Second method 11,100,000
   Average 10,810,000

3. Chemical and Industrial Storage Tanks

1. Total tons in external use 4,830,000.

2. Typical area factor for chemical tanks--200 sq.ft./ton.

3. Extra maintenance costs for chemical tanks (see Table 4) \$0.0391 sq.ft./yr.

TABLE C-1 (continued)

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3. Chemical and Industrial Storage Tanks

4. Estimate 85 percent of industrial tanks in polluted atmospheres.

5. Annual cost of controlling corrosion damage by air pollution.
4,830,000 x 200 x 0.0391 x 0.85 = $32,100,000.

Note: No alternate statistical source was found to enable an alternate calculation. In view of the good agreement in petroleum tanks, this figure should also be of the right order.

Summary:

Water	$ 3,400,000
Petroleum	10,810,000
Chemical	32,100,000
Total annual loss for external tanks	$46,310,000

Footnotes for Table C-1

Item 1. Elevated Storage Tanks

1. The total gallons of water in elevated storage for communities of 25,000 people or more (reference 40) was obtained by adding up the gallons of water listed on each of 20% of pages, selected at random, and multiplying the result by 5. Where elevated reservoirs instead of steel tanks are used, the gallons listed were omitted.

2. The data were supplied by Gerry Francis, engineering department, Columbus Waterworks. The literature study also indicated the 1 MG tank to be typical and 20,000 sq.ft. well in the range of representative tanks for designs ranging from pedestal to cylinder types.

4. The tonnage was derived from SIC statistics. From inspection of water plants it was ascertained that not all steel plate received goes into elevated storage tanks. The figure "70 percent" was a value judgment.

5. See Note No. 2.

8. Design data from both Columbus and Cincinnati water works and from a study of handbook information. See Note 2.

Footnotes for Table C-1 (continued)

2. Petroleum Product Storage Tanks

Since it is common experience to find some of the worst pollution around refineries, all the tonnage for storage tanks was considered to be exposed to polluted atmospheres .

1. Bulk storage for 1967 taken from reference (51). The storage capacity for each major product was totalled to give the 1967 figure. This was converted to the 1970 figure by assuming the growth in tankage would be the same as the rate of petroleum refinery growth for which information was available.

3. It was established by discussion with refinery engineers that 100,000 barrel storage tanks are typical for bulk storage, although some bulk tanks are several times this size. The distribution tank sizes vary widely, but the 10,000 barrel size was picked as being in the range. Although it is known that more than half of the storage capacity is in the large bulk tanks at the refinery, the 2/3 figure is purely an estimate. This judgement will not markedly affect the overall result.

4. This is a standard handbook formula which can readily be derived.

7. Derived, as outlined in Appendix A, from the SIC statistics.

8. Heavy bulk storage tanks vary widely in the thickness of plate used with the heaviest at the bottom. Plate 0.250 thick has an area factor of 196 (one side) and 0.75 inch thick, a factor of 65. The value of 120 was chosen as intermediate.

3. Chemical and Industrial Tanks

1. Derived from SIC statistics.

2. Chemical and industrial tanks vary in thickness, but in general, are much smaller than those in the petroleum industry.

   The area factor "200 sq.ft./ton" is close to that for 0.250 inch plate, one side only.

4. This value judgment is based on the observation that most of the industrial and chemical tanks are located in polluted metropolitan centers.

TABLE C-2. EXTRA MAINTENANCE PAINTING EXPENSE FOR STRUCTURAL STEEL BRIDGES IN POLLUTED AIR

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1. Estimate of bridge distribution.

For State of Ohio 650 out of 1910 bridges are in cities = 34 percent(a)

U. S. Bureau of Public Roads(b) = 25 percent

Total road mileage(c)	municipal	532,000
	rural	3,152,000
	Total	$3,684,000

No highway bridges = 563,000(d) or one every 6.5 miles

In urban areas it is estimated there is one bridge per 2.5 miles

$$\text{Percent} = \frac{532{,}000}{2.5} \div 563{,}000 = 38 \text{ percent}$$

Based on these estimates, about 30 percent of bridges are in polluted air.

2. Total tonnage 18,134,000 tons in use

Area factor for bridge steel 125 sq.ft./ton

3. Annual loss - see Table 4 for maintenance factor -

$.30 \times 18{,}134{,}000 \times 125 \times 0.0447 = \underline{\$30{,}400{,}000}$

(a) Discussion with Fred Ray, State of Ohio, Highway Department.
(b) Estimate made in 1955 by Erickson and Morgan, Reference 52.
(c) Road mileage for 1968.
(d) News release, Federal Highway Administration, October 13, 1970. (FHWA-516).

1. The notes at the bottom of the table explain the sources of information. If one studies road maps, one finds it is readily apparent that there are many more bridges in and around cities than in the open country.

2. For source of area factor, see page 207, reference 21.

TABLE C-3. CALCULATION OF AIR POLLUTION CORROSION COSTS FOR EXTERNALLY MOUNTED POWER TRANSFORMERS

1. Total area of transformers, ranging from pole size to substation sizes 556,630,000 sq.ft.

2. It is estimated that 80 percent are in polluted atmospheres.

3. For average pollution use extra maintenance cost of \$0.0167 sq.ft./year, see Table 4.

   $0.80 \times 556.6 \times 10^6 \times 0.0167 = \underline{\$7{,}450{,}000}$ per year.

1. SIC data gives numbers of each class. Designs of typical units allows one to convert to area exposed to external atmosphere.

2. Most transformers are (a) at power stations where air is often polluted, (b) substations in metropolitan districts, or on poles in urban centers where the larger uses of power are concentrated.

TABLE C-4. CALCULATION OF LOSSES, BASED ON EXTRA MAINTENANCE COSTS IN POLLUTED ATMOSPHERES FOR STREET LIGHTING FIXTURES

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1. Total tons in use - 984,574.
2. About 85 percent of external lighting in polluted areas.
3. About 15 percent of tonnage not exposed.
4. Area factor for remaining 85 percent:
   - A. 20 percent heavy gage steel - 400 sq.ft./ton
   - B. 65 percent light gage steel - 1300 sq.ft./ton
5. Maintenance factor, see Table 4, is 0.0167 sq.ft.
6. A. 0.20 x 0.85 x 400 x 985,000 x 0.0167 = 1,110,000
   B. 0.65 x 0.85 x 1300 x 985,000 x 0.0167 = 10,800,000
   $11,910,000, total annual loss.

---

1. Derived from SIC statistical data.
2. Value judgment. Most street lighting is where there is industry, commercial activity, or masses of people on the move.
3. Examination of various street lighting designs, indicates that a portion of the steel pole may be buried and that some of the construction in the lamp is not exposed. The "15 percent" figure is an educated guess.
4. Based on general observation, many lamps are mounted on wooden or other poles than steel. Thus the figure chosen here would appear conservative.

TABLE C-5. CALCULATION OF THE ANNUAL POLLUTION COSTS INVOLVED IN PAINTED OUTDOOR STEEL (METAL WORK) AND GALVANIZED STEEL

Galvanized Roofing, Siding, Roof Drainage

Maintenance factor (see Table 4) $0.0392/sq.ft. for industrial and $0.0213 for commercial districts.

1. Total tonnage of roofing, siding and drainage = 17,212,518 tons.

2. About 20 percent is used in rural areas leaving 13,750,000 tons.

3. Tonnage in industrial service = 0.40 x 13,750,000 = 5,500,000
   Tonnage in commercial service = 0.15 x 13,750,000 = 2,060,000

4. Industrial siding tonnage = 495,823

5. Prefabricated and portable steel buildings
   Total tons 12,124,871

65 percent in roofing and siding	7,890,000
55 percent of above industrial pollution	4,340,000
35 percent of above commercial pollution	2,760,000

6. Tonnage totals

A. Industrial		B. Commercial	
	5,500,000		2,060,000
	495,000		2,760,000
	4,340,000		4,820,000
	10,335,000		

7. Area factor = 1400 sq.ft./ton (one side) for 22 gauge used in industrial and 2500 sq.ft./ton for 28 gauge used in commercial applications.

8. A. 10,335,000 x 1400 x 0.0392 = $567,000,000
   B. 4,820,000 x 2500 x .0213 = 257,000,000
   Total $824,000,000

TABLE C-5 (continued)

Outdoor Gratings, Fire Escapes, and Grill Work (Industrial and Commercial)

9. Total outdoor tons = 3,107,000.

10. Estimated distribution:

10% railings	250 sq.ft./ton
50% 1/4-inch steel work	400 sq.ft./ton
40% 1/2-inch steel work	200 sq.ft./ton

11. Area factor = $\frac{10 \times 250 + 50 \times 400 + 40 \times 200}{100}$ = 305 sq.ft./ton.

12. Maintenance factor 0.0167 from Table 4.

13. Loss/year 3,107,000 x 305 x 0.0167 = $15,850,000.

14. Total area in industrial service = 64,091,720 sq.ft.

15. 64,091,720 x 0.0333 = $2,130,000 per year.

16. Total in commercial service = 41,485,382 sq.ft.

17. Use maintenance factor of 0.0167 sq.ft./yr.

18. 41,485,382 x 0.0167 = $692,000 per year.

Metal Window Sash and Frame

19. Total tons = 432,044.

20. Area factor at 100 sq.ft./ton (one side only, part of steel covered by glass and putty).

21. Maintenance factor high, estimated at $0.06 sq.ft./year.

22. 75 percent of sash in average polluted air.

23. 0.75 x 432,044 x 100 x 0.06 = $1,943,000 loss per year.

TABLE C-5 (continued)

Structural Steel--External Use

Industrial Use: 62,255,900 tons 15%, area factor 125 sq.ft./ton extra maintenance $0.0333 sq.ft.

Commercial Use: 41,815,433 tons 15%, area factor 125 sq.ft./ton extra maintenance $0.0167 sq.ft.

$62.3 \times 10^6 \times 0.15 \times 125 \times 0.0333 =$ $39,000,000 per year.

$41.8 \times 10^6 \times 0.15 \times 125 \times 0.0167 =$ $13,100,000 per year.

Public Utilities: 6,390,787 tons 65% external 125 sq.ft./ton.

$0.65 \times 6.39 \times 10^6 \times 125 \times 0.0333 =$ $17,300,000 per year.

Summary

Galvanized roofing, siding, roof drainage, prefabricated and portable buildings	$824,000,000
Outdoor gratings, fire escapes, and grill work	15,850,000
Metal doors, frames A	2,130,000
Metal doors, frames B	692,000
Metal window, sash, and frame	1,943,000
Structural Steel - External Use	
Industrial	39,000,000
Commercial	13,100,000
Public Utilities	17,300,000
Total	$914,015,000

---

1. Tonnage was derived from SIC statistical data.
2. For galvanized roofing and siding a considerable portion is used in rural shelters of all kinds. The 20 percent figure is a value judgment.
3. These breakdowns also are value judgments. Much more of the tonnage is known to be in industrial use. Galvanized roofing and siding also is used, to some extent, in less affluent residential areas.
4. SIC sources.
5. Part of the metal used in portable steel buildings is not exposed to the atmosphere. It was judged that about 65 percent is. More of these buildings are in industrial service than in commercial service. The distribution is a value judgment based on discussions with fellow staff specialists in housing.
7. Area factors of 1400 and 2500 correspond to 22 and 28 gauge, respectively.
9. Derived from SIC sources.

TABLE C-5 (continued)

10. Educated guess based on a study of fire escapes and outdoor grill work.

14,16. Calculated from SIC data.

15,17. Maintenance factors from Table 4.

19. Calculated from SIC data.

20. Educated guess based on observation of steel sash and frame construction in industrial buildings.

21. This estimate is considered conservative, in view of the extremely high labor costs in preparing the surface and painting steel sash.

22. Since most of the steel sash is used in industrial and commercial applications, and not in residential this estimate is a value judgment.

TABLE C-6. CALCULATION OF AIR POLLUTION COSTS FOR GALVANIZED POLE-LINE HARDWARE

1. Total tons of pole-line hardware products, transmission hardware and related products. 4,062,735 tons.

2. About 75 percent of total is estimated to be pole-line hardware.
   0.75 x 4,062,735 = 3,040,000 tons.

3. Area factor for pole-line hardware = 450 sq.ft./ton.

   For typical pole with 4 sq.ft. of hardware, number of poles in use is

$$\frac{3,040,000 \times 450}{4} = 342 \times 10^6$$

4. From zinc statistical data, if it estimated that there is 165,000 tons of zinc consumed in galvanizing pole-line hardware still in use. At a bath efficiency of 50 percent, this is 82,500 tons of zinc in use. At a coating weight of 2 oz./sq.ft. this equals 8 oz./pole

$$\frac{87,500 \times 2,000 \times 16}{8} = 330 \times 10^6 \text{ poles}$$

5. Average no. of typical poles = 336×10^6.

6. Some 40 percent of poles are exposed to urban conditions (see footnote).

7. In average polluted air, hardware lasts typically 15 years whereas the wooden pole last about 22.5 years. Thus for service in polluted air, pole-line hardware is replaced once.

8. Cost of regalvanizing, per pole at $0.55/sq.ft.
   4 x 0.55 = $2.10
   Cost on weight basis, at $0.11/lb.

$$\frac{2,000 \times 4 \times 0.11}{450} = \$1.96$$

   Cost of regalvanizing is about $2.00 per pole.
   Labor cost of installation and removal $25.00 per pole.

   27.00 ÷ 22.5 = $1.20/year/pole

9. Annual loss based on replacement and regalvanizing is $.40 \times 335 \times 1.20 \times 10^6$ = $161,000,000

---

1. Calculated from SIC statistics.

2. No breakdown in the SIC is given for related products: (see item No. 1). Some of this hardware may be items exposed on the pole, although only partially exposed, such as bolts and nuts. Brackets, on the other hand, are almost entirely exposed. The figure "75 percent" is a value judgment.

3. Pole-line hardware with a thickness of 3/15-inch would have an area factor of 524 and for 1/4 inch it would be 392 sq.ft. The factor, 450, was chosen as intermediate in this range.

6. This figure is an educated guess. Personal observation suggests that there may be five times as many poles per rural customer as are required for urban customers. On this basis, if 20 percent of the population accounts for 100 parts of the total poles, and 80 percent, 80 parts, the percent poles in urban areas would be 80 ÷ 180 or 44. The figure 40 percent was used in the calculation.

7. According to a fellow staff member who has specialized in wood preservation, the life of impregnated wooden poles is from 20 to 25 years.

8 The cost of regalvanizing is given in Reference 32. Note that the cost on a weight basis, obtained from Brown Steel Galvanizing Company of Columbus, Ohio, is almost the same.

Labor costs include set-up time, removal of old hardware, and installation of new. Two men are required and the labor estimate of $25 includes overhead.

TABLE C-7 . CALCULATION FOR CHAIN-LINK FENCE

1. Total tonnage of galvanized chain-link fence in service-4,018,980 tons.

2. Sizes vary from 3 to 12 feet in height. Typical height is 6 feet. Typical wire gauge is No. 9.

3. 80 percent of chain-link fencing is used in industrial and commercial areas.

4. The weight of steel in a 100-foot length of 6-foot high fence wire diameter = 0.148″, weight = 0.0578 lbs/ft. One square foot of fence with 2-inch squares is equal to 12 feet of wire.

   600 x 12 x 0.0578 = 415 pounds of fencing/100 feet

5. Total number of 100-foot lengths of 6-foot high fence

   $$\frac{4{,}018{,}980}{415} \times 2{,}000 = 19.35 \times 10^6$$

6. Taken at 80 percent in polluted air = 15.5×10^6 100 ft. lengths.

7. System life of posts is 30 years, but fencing is 20 years. Rural zinc coating life is 20 years. Polluted life varies, 8 years is typical.

8. If system is painted, roller coating costs would be

   First coat 275 sq.ft., labor 4.72, paint 3.96 = 8.68 or .0316/sq.ft.
   Second coat 375 sq.ft., labor 4.72, paint 4.66 = 9.38 or .0221/sq.ft.
   Cost per sq.ft. = .0537 Rural life of galvanized wire - 20 years.
   Life in polluted air = 8 years.

   Rural exposure - no maintenance for 20 years.
   Polluted exposure two coats at 8, 14 years.

   Extra cost/sq.ft. for 20 years = 2 x .0537

   Extra annual cost/sq.ft./yr = .0054

9. Posts and Fittings - per 100-foot length, 6-foot high fence

Amount needed	size	Area Calculation	Sq.ft.
1	3.5 in. diameter corner post	$\frac{\times 3.5 \times 6}{12}$	5.5
8	2.5 in. diameter fence post	$\frac{8 \times \quad \times 2.5 \times 6}{12}$	31.3
10	1.6 in. diameter rail post	$\frac{10 \times 10 \times \quad \times 1.625}{12}$	42.5
	Add 10% for special fittings		8.0
		Total	87.3

TABLE C-7 (continued)

10. Annual extra cost per 600 sq.ft. fence wire and 87 sq.ft. posts.

Wire 600 x .0054 = \$3.24 (see Item No. 8)
Posts 87 x .0233 = 2.03 (see Table 4)

11. About 25 percent of owners maintain fencing by painting.

$.25 \times 15.5 \times 10^6 \times 5.27 =$ \$20,400,000.

12. Replacement cost of entire fence. No maintenance, last ten years rusty.
A. Rural life 20 years plus 10 years rusty = 30 years
B. Polluted life 8 years plus 10 years rusty = 18 years

13. Cost of fence and installation per 100 feet is about \$440.

A. Annual cost 440 ÷ 30 = \$14.65/100 ft./yr.
B. Annual Cost 440 ÷ 18 = \$24.45/100 ft./yr.

14. Pollution cost per year is equal to difference \$9.80. If 25 percent of owners replace, the annual extra cost is $.25 \times 15.5 \times 10^6 \times 9.80 =$ \$38,000,000.

15. Replacement of galvanized wire and painting posts.(1)
Rural Cost = no wire replacement, last 10 years rusty
Pollution cost = two wire replacement (each wire rusty for two years before replaced).
Extra cost for 30 years = two wire replacement + two paintings of posts.

Cost of 100 feet wire = \$ 54.00
Labor and delivery = 72.00
Total \$126.00

Total cost of two extra replacements \$252.

Cost of two paintings for 87 sq.ft. of posts.
$2 \times 87 \times (.50 \times .40) =$ \$158

16. Total extra cost, 30 years = 252 + 158 = \$410

Total annual extra cost per 100 feet of 6 foot fence = 410 ÷ 30 = \$13.65.

If 50 percent replace galvanized wire, then annual pollution cost is:
$.50 \times 15.5 \times 10^6 \times 13.65 =$ \$106,000,000.

17. Summary of annual galvanized fence costs.

Percent	Annual Extra Cost Basis	Item No.	Annual Pollution Loss
25	maintenance by painting	11	\$ 21,800,000
25	let fence rust, then replace	14	38,000,000
50	Replace wire(1), paint posts	16	106,000,000
			\$165,800,000

(1)Although wire fencing can be regalvanized, current handling costs, set-up time, etc., usually does not make it pay. Present practice is to buy new wire.

Table C-7

1. Data derived from SIC statistics.

2. See Reference NA-1.(54) Other details on chain-link fencing were obtained from catalogs, from dealers in Columbus and Cincinnati, and from the trade magazine "Fence Industry".

3,6. According to Columbus and Cincinnati dealers, only a small portion of the total tonnage goes into residential use and almost none into rural service. This is a value judgment, based on the above discussions.

4. These calculations are for 9 gauge wire, the most common size used by industrial plant and institutions for general security purposes.

7. System life is provided by the IRS, see Reference 7.

8. These costs were derived using older data in Reference 32 as a guide. If overhead were included the costs would be higher.

9. These are the sizes of posts and railings recommended for 9 gauge chain-link fencing in catalogs.

11,12,13,14,15,16. For purposes of computation, it was assumed that 25 percent of owners prolonged life by maintenance painting, 25 percent let fence rust then replaced entire fence and 50 percent replaced the wire only and maintained the posts and rails. A study of fencing practice indicates all three methods are followed, but the proportions chosen are an educated guess.

15. Cost of 100 feet of wire provided by a local fence manufacturers. Labor and delivery charges are estimated.

TABLE C-8. CALCULATION OF AIR POLLUTION CORROSION COSTS FOR GALVANIZED WIRE ROPE

First estimate based on steel statistics

1. Total tons of wire rope in service - 6,301,000.

2. As shipped value - $,015,000,000.

3. Cost per ton - $653 (about $0.32/lb.).

4. Rural life = 20 years 635/20 = $31.7 ton/yr.
Industrial life = 8 years 635/8 = $79.4 ton/yr.
$79.4-$31.7 = $47.7 extra cost per year per ton charged to pollution.

5. About 40 percent of wire exposed to pollution.
6,301,000 x 0.40 x 47.7 = $120,000,000 per year.

Second estimate based on zinc statistics

6. Total zinc consumed in wire galvanizing baths - 1955 to 1969 = 572,213 tons.

7. At bath efficiency of 50% leaves 286,107 tons.

8. Typical wire size - 0.120 inch diamter.
Area per 1,000 feet of length = $\frac{\text{x } 0.120}{12}$ x 1000 = 31.4 sq.ft.

9. Zinc wire coating, Class A, double galvanized = 0.85 oz/ft^2.
31.4 x 0.85 = 26.6 oz/1000 feet.

10. A 3/8th stranded wire rope has 7 strands.
7 x 26.6 oz. = 186 oz./1000 ft. wire rope.

11. Total number of 1,000 foot lengths in service:
$\frac{286{,}107 \times 2{,}000 \times 16}{186} = 49.3 \times 10^6$ 1,000 foot lengths of wire cable.

12. 1968 price of 3/8th 7-wire strand = $62/1,000.
1970 price (estimated) $70/1,000.

13. Rural life at 20 years 70/20 = $3.50/yr.
Industrial life at 8 years 70/8 = $8.75/yr.

14. $8.75 - $3.50 = $5.25/yr/1,000 feet extra cost because of pollution.

15. 49.3 x 10^6 x 0.40 x 5.75 = $103,500,000 per year.

Summary: Both values are of same order. Taking an average of the two = $111,800,000 per year.

Table C-8

1,2,3 Derived from SIC data

5. Much of the galvanized wire rope is used in rural andmarine applications, where man-made pollution is not the major factor. The selection of "40 percent" is an educated guess.

6. Zinc statistics taken from Reference (49).

TABLE C-9. CALCULATION OF THE EXTRA MAINTENANCE

Expense for Galvanized Steel Power Line Transmission Towers Exposed to Air Pollution.

1. System life 30 years.
2. Total tons in use 1,449,000.
3. Typical weight 7.5 tons.
   No. of typical towers = 1,449,000 ÷ 7.5 = 194,000
4. According to a survey 12.5 percent are in contaminated air.
   0.125 x 194,000 = 24,300 typical towers subject to pollution.
5. Area of typical tower = 2500 square feet. Maintenance factor for galvanized towers (Table 4) is $0.0233/sq.ft./year.

   Annual loss is estimated to be:

   24,300 x 2500 x 0.0233 = $1,480,000.

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1. Reference 7.
2. Determined from SIC statistics.
3. See Reference 53.
4. See Reference 54.
5. See Reference 53.

TABLE C-10. SUMMARY OF PRINCIPAL DATA USED IN TABLES C-1 to C-9

	Water Tanks	Petroleum Tanks	Industrial Tanks	Bridges, Rail and Highway	Power Transformers	Street Lights	Metal Work Galvanized	Metal Work Painted	Pole-Line Hardware	Chain-Link Fence	Wire Rope	Transmission Towers
Metal Economics												
Tons Shipped(1)	142	201.4	511.4	717.6		54.3			157.6			
Inventory(2)	7,100	1,950	4,830	18,134	12,316	984.6	10,335		4,063	4,019	6,301	209.7
Dep. Value(5)	10,659	695	1,935	5,043	12,316	1,221			1,262	577.6	2,008	1,165
Depreciation %	2	9	9	3.3	3.3	5.0	2.2	2.2	3.3			3.33
Life, years(9)	50	11	11	30	30	20	45	45	22.5(30)	20/30	20	30
Capacity	11x40^9 gal	477x10^6 bar.		657,000(4)	556.6(3)			64,091/ 41,485(8)			49.3(10)	194,000(11)
Area Factor(6)	125	120	200	125		400/1300	1400/ 2500	various		2,900		
Pollution-% or exposure(7)	80	100	85	30	80	85	80	40/15	30	80	40	12.5
Cost,$/sq.ft./yr	0.0167	0.0473	0.0391	0.0447	0.0167	0.0167	0.0392/ 0.0213	0.0333/ 0.0167				.0.0233
Calculations in Table	C-1	C-1	C-1	C-2	C-3	C-4	C-5	C-5	C-6	C-7	C-8	C-9
Total Annual loss $\$ \times 10^6$*	3.4	10.81	32.1	30.4	7.45	11.91	824.	90.02	161.	165.8	111.8	1.48

*For all twelve categories, the total of the annual losses is $1.45 billion.

Footnotes for Table C-10

1. Tons, in thousands, as derived from SIC statistics, shipped in 1963.
2. Tonnage of tankage in situ that remains in service, i.e., not yet depreciated using life of system as determined by IRS.
3. Area in millions of square feet.
4. Total number of highway and railroad bridges in service, see Table C-2.
5. Depreciated value, in thousands of dollars, of tankage still in service.
6. Area factor is given in square feet per ton. In some cases, e.g., steel plate for tanks, it is for one side only.
7. This figure is the estimated percent of total area exposed to pollution.
8. Area in thosands of square feet for metal doors and frames in (a) industrial and (b) commercial service. Other items are given in Table C-5.
9. Life as determined by IRS tables, see Reference (7).
10. Millions of 1,000-foot lengths of equivalent 3/8ths inch 7 strand cable as calculated in Table C-8.
11. Number of "average" towers as calculated in Table C-9.

TABLE C-11. COMPARISON OF METAL ROOFING FOR SERVICE IN HIGHLY POLLUTED ATMOSPHERE.(a)

Material	Years Life Polluted air(b)	Gauge(c)	Thickness	lbs/ cu.in.	lbs/ sq.ft.	Mill Price $/ pounds	$ Cost/ sq.ft.	Extras/ sq.ft. Inst.	Labor	Installed cost, $/ sq.ft.	$ Cost/ yr./ sq.ft.
Galvanized Steel	10	22	33.6	0.292	1.406	.10	.14	--(d)	.35	.49	.049
Aluminum	50	18	40.3	0.098	.57	.48	.37	--(d)	.30	.67	.013
Copper	100+	28	12.6	0.322	.58	.92	.53	.20(d)	.40	1.11	.011
Terne Plate	50	26	15.9	0.293	.67	.12	.08	.45(d)	.40	.93	.019

Material	$ Cost/yr/sq.ft. Above Rural Galvanized(e)	Annual Charge to Pollution $ per Square Foot	Percent Saving Using Cost of Galvanized Steel in Polluted Air as Reference
Galvanized Steel	0.035	0.035	----
Aluminum	-0.001	none (saving)	73.5
Copper	-0.003	none (saving)	77.5
Terne Plate	0.005	0.005	61.3

(a) Annual costs are based on original installation expense, life of system, and no added maintenance.

(b) Life in years as originally installed.

(c) Brown and Sharp gauge, except for galvanized steel where special sheet gauge is used.

(d) Both galvanized steel and aluminum are considered self supporting, whereas extra expense is allowed for copper and terne plate to provide backing for support. Terne plate is painted at the time of installation.

(e) Life of galvanizing in rural environment is 35 years. Rural cost is installed cost divided by year = \$0.49 ÷ 35 = \$0.014/sq.ft./year.

TABLE C-12. COMPARISON OF ALUMINUM WITH GALVANIZED STEEL SIDING, 1969

1. Aluminum siding varies in thickness from 0.024 to 0.040 inch. Typical thickness is equal to 0.0320 inch (20 gauge) and weights 55 lbs/100 sq.ft.

2. Total production of aluminum siding for 1969 is 53,000,000 lbs.

3. The equivalent area for this weight is $53 \times 10^6 \div 0.55 = 96 \times 10^6$ sq.ft.

4. Using roofing data in Table 9 as a guide, the installed cost of 0.320 inch thick aluminum would be $0.59/sq.ft. and for 0.276 inch thick galvanized $0.43/sq.ft.

5. The installed cost for 96×10^6 sq.ft. would be:

Aluminum	$56,700,000	Life = 50 years, industrial or rural
Galvanized	$41,300,000	Life = 10 years, industrial, 35 years rural
Premium=Difference	$15,400,000	

6. The annual costs would be:

Aluminum, Industrial	$1,133,000
Galvanized, Industrial	$4,130,000
Galvanized, Rural	$1,180,000

7. Annual charge to pollution using rural galvanized as reference.

Aluminum - none		(small saving)
Galvanized	$2,950,000	

3

TABLE C-13. COMPARISON OF THE COSTS OF USING BARE SELF WEATHERING STEEL AND PAINTED CARBON STEEL FOR BRIDGES EXPOSED TO POLLUTION

1. Annual maintenance cost for painted carbon steel, 30 year life (as in bridges), area factor 125, and paint costs from Table 4.

Carbon Steel. Rural Atm., Cost/Ton/Yr = $\frac{125 \times 1.30}{30} = \$5.40$

Polluted Atm., Cost/Ton/Yr = $\frac{125 \times 2.64}{30} = \$11.00$

2. Comparison of carbon steel and self weathering steel on an installed basis.(43) Costs are per ton.

	Carbon Steel	Self Weathering Steel	
Mill Price	$131		
Erection	184	184	
Total	$371	264	
		448	(less allowance for
		- 45	higher strength)
Total		$403	(per ton of carbon steel replaced).

3. Annual premium for self weathering steel per ton of carbon steel replaced.

$\frac{403 - 371}{30} = \$1.07\text{/ton/year}$

4. Comparison between painted carbon steel in rural environment and unpainted self weathering steel in polluted environment.

   (a) self weathering steel - annual premium/ton = $1.07.
   (b) painted carbon steel - annual maintenance/ton = $5.40.

5. Annual saving per ton of carbon steel replaced in using bare weathering steel and costs in Item 4.

   5.40 - 1.07 = $4.33/ton/yr.

6. Comparison between painted carbon steel in polluted environment with bare self weathering steel in polluted environment.

   Carbon Steel (item No. 1) Cost/ton/yr = $11.00
   Self weathering steel (item No. 3) cost/ton/yr = $1.07

7. Annual saving per ton of carbon steel replaced using costs in Item 6.
   $11.00 - 1.07 = $9.93/ton/year.